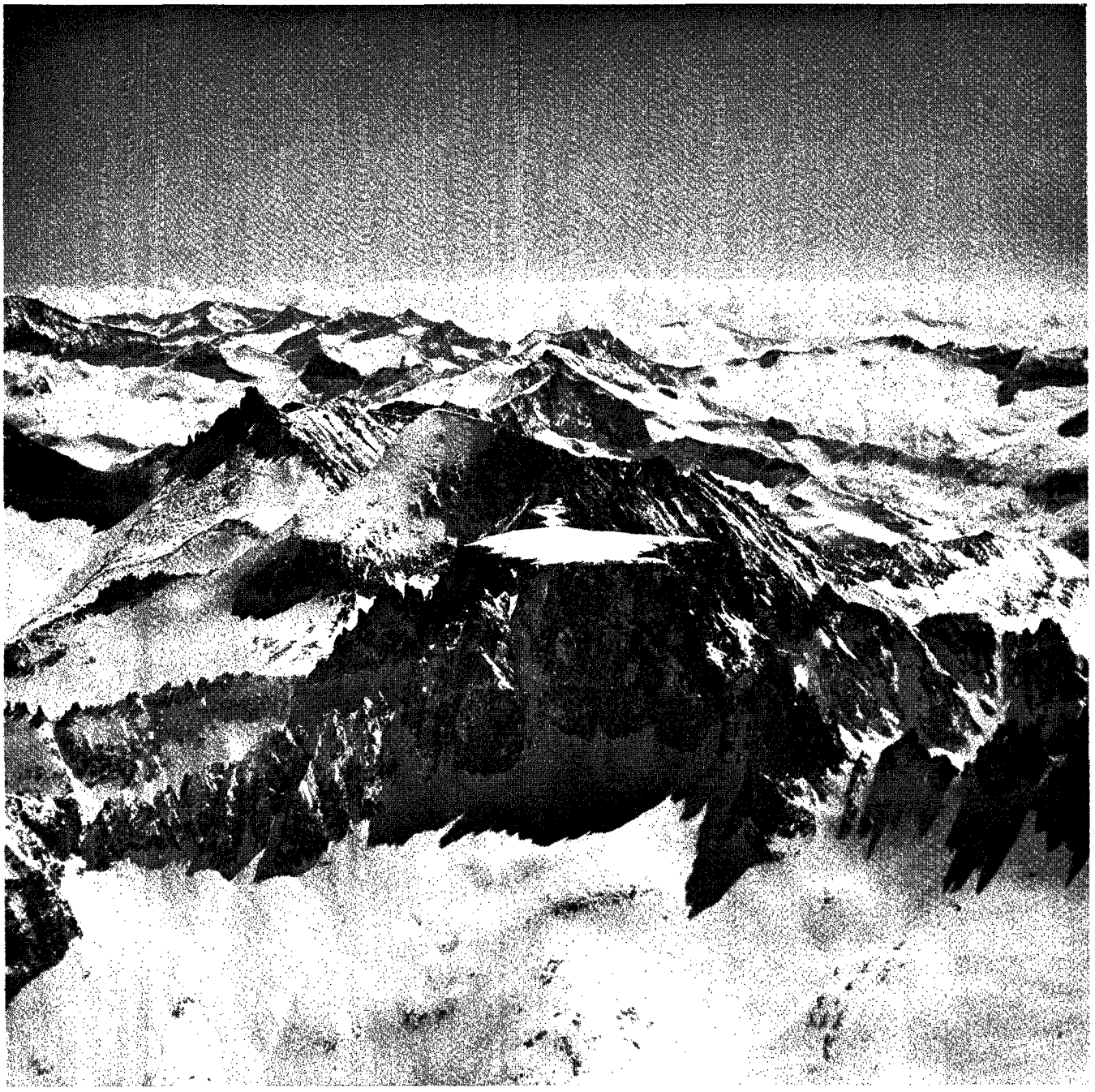
WMA



The Journal of Weather Modification

Volume 5 Number 1 May 1973

Cover Photograph

This view looking south shows flat-topped Mt. Darwin and the headwaters of three major streams in the Sierra Nevada Mountains of California. The San Joaquin River drains away to the right. The Kings River watershed in the center beyond Darwin drains westward and Bishop Creek drains easterly out of the photo to the left. The regions have great historic significance for weather modification operations in the United States. The first long term weather modification project in U.S. began over Bishop Creek with the initial seeding flight logged on 2 February 1948 under the sponsorship of the California Electric Power Company. The Southern California Edison Company followed with their historic project early in 1950 over the San Joaquin Watershed and the Kings River Conservation District initiated cloud seeding operations over the upper Kings River Watershed in late 1954. Both the Kings River and San Joaquin River Projects have been operated continuously since their inception with the primary objective of increasing precipitation (rain and snow) for hydro power generation in the mountains and irrigation requirements in the Valley.

Photograph by Thomas J. Henderson,
Atmospherics Incorporated
Fresno, California

Weather Modification Association
Mr. Hoyt Hart, Executive Secretary
7080 Via Ramada
San Jose, California 95139
(408) 227-8463

Additional Copies available at $6.00 each
Libraries and non-members $15.00 each

"NON-REVIEWED"

- THE JOURNAL OF WEATHER MODIFICATION -

WEATHER MODIFICATION ASSOCIATION

Volume V Number 1 June 1973

Table of Contents

A CHALLENGE TO THE WEATHER ENGINEERS . . . . . 1 - 6
Vincent J. Schaefer

THE SOUTH DAKOTA WEATHER MODIFICATION PROGRAM . . . . . 7 - 23
Merlin C. Williams

OBSERVED UPDRAFTS AND HAIL INSIDE A THUNDERSTORM . . . . . 24 - 29
W. R. Sand, R. A. Schleusener and D. J. Musil

HAIL SENSING AND SMALL-SCALE VARIABILITY OF WINDBLOWN HAIL . . . . . 30 - 42
Stanley A. Changnon, Jr.

PROJECT HAILSTOP: A REVIEW OF ACCOMPLISHMENTS TO DATE . . . . . 43 - 55
Peter W. Summers

TENTATIVE RESULTS OF FOUR YEARS OF RANDOMIZED SEEDING IN THE JEMEZ MOUNTAINS 56 - 83
C. G. Keyes, Jr., F. D. Stover, R. D. Wilkins and M. Lentner

SOME IMPRESSIONS OF WEATHER MODIFICATION DEVELOPMENTS OVERSEAS . . . . . 84 - 87
Jeremy M. Gosnell

SEEDING SINGLE CUMULUS CLOUDS IN RHODESIA WITH SILVER IODIDE: 1968-69 88 - 102
D. L. McNaughton

AN AREA CLOUD SEEDING EXPERIMENT IN THE NORTH OF RHODESIA, 1970-71 103 - 115
D. L. McNaughton

RESULTS FROM A 7 YEAR CONTINUOUS SEEDING WITH A GROUND GENERATOR ON THE FRENCH ATLANTIC COAST 116 - 125
Jean Dessens and Jean-Pierre Lacaux

FOG CLEARING WITH HELICOPTER DOWNWASH . . . . . 126 - 132
David H. Dickson and Walter S. Nordquist, Jr.

RESULTS OF THE BOWMAN-SLOPE HAIL SUPPRESSION PROGRAM 133 145
A. F. Butchbaker

THE USE OF HIGHLY CHARGED HYGROSCOPIC DROPS FOR FOG DISPERSAL . . . . 146 - 160
John W. Carroz, Pierre St.-Amand and Donald R. Cruise

MINICOMPUTER PROGRAM TO PREDICT FOG BREAK-UP TIMES . . . . . 161 - 165
Harold E. Cronin

AIRBORNE JET SEEDER SOLUTION BURNER . . . . . 166 - 177
John Carroz

Table of Contents

	Page
PARTICLE SIZE AND NUCLEI ACTIVITY CHARACTERISTICS OF A LOW OUPUT AgI GENERATOR *Briant L. Davis, Donald N. Blair, L. Ronald Johnson and Pierre St.-Amand*	178 - 216
A BENCHMARK NETWORK FOR ICE NUCLEUS COUNTS *Paul A. Allee*	217 - 221
FIELD COMPARISONS OF ICE NUCLEUS MEASUREMENTS BY THREE METHODS *C. A. Grainger and A. B. Super*	222 - 237
RAW AND IODINE TREATED AUTOMOBILE EXHAUST AS A SOURCE OF ICE NUCLEI *Lewis O. Grant and Myron L. Corrin*	238 - 248
THE STIMULATION OF RAIN IN YUGOSLAVIA *Drazen Poje*	249 - 253
PHENOMENA OF PERSISTENCE OF ARTIFICIAL ICE-NUCLEI CONCENTRATION *Paolo Petti*	254 - 260
THE RELATIONSHIP OF SOCIO-DEMOGRAPHIC CHARACTERISTICS AND ATTITUDES TOWARD WEATHER MODIFICATION: THE SOUTH DAKOTA STUDY, 1972 *Barbara C. Farhar*	261 - 276
FACTORS RELATED TO ATTITUDES TOWARD WEATHER MODIFICATION PROGRAMS *Orville Lanham and Jerome Rosonka*	277 - 295
APPLYING ULTRA LONG RANGE WEATHER PREDICTION AND WEATHER MODIFICATION TO ENVIRONMENTAL MANAGEMENT *Irving P. Krick*	296 - 317
REPORT ON RAPID CITY FLOOD OF JUNE 9, 1972 *Pierre St.-Amand, Ray J. Davis and Robert D. Elliott*	318 - 346
HOW TO TREAT A PAINFUL PROBLEM OR CLOUDSEEDING ANYONE? *Anonymous*	347 - 348
ADVERTISEMENTS	349 - 352
CONSTITUTION AND BYLAWS OF THE WEATHER MODIFICATION ASSOCIATION	353 - 356
QUALIFICATIONS AND PROCEDURES FOR CERTIFICATION BY THE WEATHER MODIFICATION ASSOCIATION	357 - 359
WEATHER MODIFICATION ASSOCIATION - OFFICERS	360

Table of Contents

	Page
WEATHER MODIFICATION ASSOCIATION - CERTIFIED AND HONORARY MEMBERS	361
WEATHER MODIFICATION ASSOCIATION - CORPORATE MEMBERS	362
WEATHER MODIFICATION ASSOCIATION - ASSOCIATE CORPORATE MEMBERS	363
WEATHER MODIFICATION ASSOCIATION - INDIVIDUAL MEMBERSHIP DIRECTORY	364 - 371
BACKGROUND OF THE WEATHER MODIFICATION ASSOCIATION	372
INSTRUCTIONS - ADVERTISEMENTS AND MEMBERSHIP DUES	373

A CHALLENGE TO THE WEATHER ENGINEERS

Vincent J. Schaefer

Atmospheric Sciences Research Center
State University of New York at Albany

Over the years since I dispensed six pounds of dry ice fragments into a supercooled cloud over western Massachusetts on November 13, 1946, I have watched with interest and a degree of frustration the development of weather engineering.

In retrospect, there are not many new aspects of cloud modification which have developed in the past quarter centry. As I pointed out in Volume 4 of the Journal of Weather Modification (1) dry ice, silver iodide, water and salt seeding had been evaluated in a semi-quantitative manner by our Project Cirrus group in the late 1940's. By 1950 we had considered and discarded statistical methods in favor of physical evaluations. We did this not because we were unfamiliar with the importance of statistical methods in their proper place, but because, as Langmuir had pointed out (2), most weather developments including individual cloud systems are controlled to a considerable degree by divergent phenomena.

In my opinion, it is a fruitless endeavor to assume that the toss of a coin or the use of a set of random numbers can be very useful in establishing whether or not cloud seeding "works". Utilizing all of our nearly incredible scientific and engineering know-how, we should be able to evaluate chemical and physical reactions in the atmosphere with a more objective and quantitative approach.

At Yellowstone National Park during the winter periods of 1960 through 1970 (3) we were able to show that in an area of more than 50 square kilometers it was possible to predict the kinds of reactions, the number, sizes and types of ice crystals that would form, their arrival times at our observation sites, the optical effects that would occur, and the related phenomena that were induced by various applications, techniques, and types of cloud seeding materials.

By utilizing this unique natural laboratory, we were able to convince many doubters that predictable cloud seeding effects actually do occur in the atmosphere if certain physical conditions are present. Our Yellowstone experiences clearly demonstrated that there are certain places over the earth where it is not necessary to devote ten, twenty, or a hundred years to establish the verity of a controlled phenomenon in the "natural" atmosphere.

Unfortunately, it takes more than just the identification of unique natural atmospheric laboratories to solve our problems. It also requires astute, imaginative, knowledgeable, enthusiastic, innovative and industrious individuals at every level of an operation to establish the effectiveness of a field program. Often, it also requires the occurrence of serendipitous events and an observer smart enough to take advantage of their happenings!

This was clearly noted during many of our Yellowstone operations. Despite the fact that each year I sought out the best scientists and engineers in the field of cloud physics and related subjects, some of the most vocal of the fraternity never could arrange their affairs to devote a week in the field. Others, who did attend, were not always present during the very cold early dawn periods when the most interesting reations occurred. Some had so little field experience and "know-how" that they were unable to savor the spectacular phenomena occurring all about them.

Fortunately, the Yellowstone Expeditions were an invaluable training ground and exposure area for a hard core of scientists and engineers interested in atmospheric reactions. The friendships which developed, the scientific and engineering information exchanges which occurred, the demonstratable techniques, and the unique long range effects of the seminars and field activities that were a feature of Y.F.R.E. have exerted an important and lasting effect with some of the key individuals in our profession.

Where are the other "Yellowstones"? There are many! They range from such places as Kericho in Kenya for hail, the San Francisco Peaks in Arizona and the Magdalena Mountains in New Mexico for thunderstorms, the Eastern and Western Coasts and some inner valleys for fog, the lee of the Great Lakes and the Japanese Sea for "lake effect" snowstorms, the summits of Whiteface Mountain in New York, Mount Washington in New Hampshire, Chalk Mountain in Colorado, Elk Mountain in Wyoming for supercooled clouds, etc., etc.

There is another such area of importance that I would like to mention which is available to nearly everyone interested in cloud and weather modification. This region is at the base of the stratosphere.

Twenty-five years ago we first proposed making studies of this important area. In fact, it was for this reason the Project Cirrus was given that name. In 1947 I suggested to our associates from the Army, Navy and Air Force that the major research theme of our efforts (which occurred during the period of 1947-1952) could best be encompassed by a broad understanding of the mechanism causing the conversion of supersaturated moist air and supercooled clouds to the formation of cirrus type clouds. These mechanisms seemed extremely important whether they occurred naturally or were produced by seeding operations conducted at the tropopause or lower cloud levels in the atmosphere. Thus was Project Cirrus formed.

One of our early experiments involved the seeding of thin supercooled clouds with one aircraft and the sampling of ice crystals produced using a following plane. Another experiment utilized the upwind seeding of a wave cloud and the observation of crystals emerging at its down wind edge. A Third, and frequent operation, was the release at ground level of small balloons carrying dry ice in order to detect atmospheric regions supersaturated with respect to ice. A fourth spectacular experiment was the production of large areas of false cirrus by crushed dry ice line seeding of air supersaturated with respect to ice (4). In the fall of 1946, shortly after my first seeding flight, I converted a supercooled ground fog to ice crystals. These crystals then grew and fell to the ground causing the fog to dissipate. This experiment was followed by liquid CO_2 seeding under the base of a supercooled convective cloud. This produced fantastic numbers of ice embryos which then were lifted by convection into the cloud to initiate a local snow storm (5).

Cirrus clouds come from various sources. Some occur when moisture in the air exceeds saturation with respect to ice at temperatures colder than -40C. This produces homogeneous nucleation in concentrations greater than 1 x 10^{10} ice embryos per cc.(6) This, of course, occurs on a global scale. At other times the "cirrus" emerges from the top of large cumulus developments. In some instances this too can produce cirrus crystals from homogeneous nucleation. Langmuir was one of the first to point out this phenomenon and in typical fashion he gave it the very descriptive name - a "ring crown cloud." (7) He first described these clouds following a field trip to Central America during which time he also devised his penetrating ideas on water seeding in the chain reaction phenomena which occurs frequently in convective clouds.(8)

Other "false cirrus" ice crystal streamers rising from convective clouds are certainly caused by heterogeneous nucleation. The occurrences of this nucleation mechanism, as compared with homogeneous nucleation, is a variable factor dependent to a major degree on the nature of the fine particles that move into such clouds from the lower levels of the atmosphere. It is quite likely (but not yet proved) that some of these probably come from lead iodide produced by an atmospheric reaction which occurs between iodine molecules and sub-microscopic particles of lead compounds produced by automobile exhaust.(9)

Anyone even slightly observant must be aware of the widespread nature of cirrus clouds that dominate the afternoon sky in the Southwest, the high plains east of the front range of the Rockies, and in other parts of the world where convective clouds occur. (10)

Those who fly and look out the window must certainly be aware of the extensive nature and massive volumes occupied by cirrus clouds. Thanks to the radar surveillance of flight paths, jet aircraft seldom encounter the core of large convective clouds. Thus, they often fly parallel to the anvil streamers of these clouds and it is possible to observe how extensive they can be. I have seen anvil cirrus extending for several hundred miles from their point of origin. Satellite cloud photographs often depict them and verify their frequent and extensive dimensions.

Another type of false cirrus is commonly produced along the jet routes encircling the earth. To those of us who enjoy viewing the geomorphic forms of the earth, or the ever-changing cloud patterns, or the state of the sea over the oceans, this can be a very aggravating phenomenon. In my last four jet flights from the west coast to Chicago, I have been prevented from obtaining good photographs of Lake Powell, Navajo Mountain, Monument Valley and the San Juan Mountains due to a translucent veil of ice crystals produced by the condensation trail of aircraft preceeding the one on which I was flying.

In recent fine particle monitoring flights which I have made from Chicago to Honolulu and the Fiji Islands, I was able to easily detect the fine particles of these jet exhausts and what I believe is the presence of nitrogen dioxide emmitted by the aircraft flying along our jet route.

As mentioned earlier, particles producing cirrus clouds, especially of the type that emerge from the top of convective clouds, consist of condensed water droplets which, during a portion of their existence, were in the super-

cooled state. Thus the "false cirrus" cloud is visible evidence that the precipitation process was not completely effective. In fact, at times the precipitation effectiveness is zero with nearly all of the cloudiness in the upper portions of a convective cloud being converted to ice crystals which are carried in long streamers for many miles downwind of the area where the cloud originally formed.

Last summer I observed and photographed such an occurrence. A large convective cloud mass developed over the Cinder Hills east of the San Francisco Peaks near Flagstaff, Arizona. The cloud was so large I expected to hear that severe flash flooding would be reported in the dry washes which run into the Little Colorado between East Flagstaff and Leupp and that the Grand Falls of the river would have a heavy flow. The cirrus streamer from the spreading anvil of that cloud extended beyond Black Mesa and Kayenta. At sunset, ten hours after I first saw its formation stages, the cirrus development was still the dominant cloud mass of the mid-June sky over northern Arizona. Upon returning to Flagstaff that evening I learned that, except for very light showers, no precipitation had occurred in the area. The Little Colorado River and its Grand Falls remained dry.

This was a fairly typical occurrence in northern Arizona. Clouds that look like they should produce heavy rain often produce little if any precipitation. Occasionally, virga will develop which doesn't reach the ground. During the mid-July to mid-August period such clouds may produce twenty to thirty minutes of heavy rain or hail, but the dominant feature of such activity is the extensive false cirrus streamers which almost always form and constitute a spectacular portion of the sunset skies of Arizona, Colorado, New Mexico, Utah and other regions of the Southwest.

Several years ago I published a paper with Roger Cheng which suggested the mechanism causing the extensive and rapid glaciation of convective clouds.(11) Such rapid glaciation we believe is caused by the ejection of frost crystals resulting from sublimation and electrical effects which form in air saturated with water on large precipitation particles such as hail or graupel that fall through rising convective clouds. (Note: There is a very interesting informative aspect of ice crystals clouds which merits further study. It appears to me that cirrus clouds which form by homogeneous or heterogeneous nucleation, in which the primary nucleus has a cross section of less than 0.01 microns, produce optical effects such as the 22^{o} or 46^{o} halo and the undersun. Ice nuclei, having a larger cross section, tend to form irregular shaped crystals or rounded ice particles which rarely, if ever, are capable of producing such optical effects. False cirrus and contrail cirrus, as well as cirrus produced by volcanic dusts and ordinary dust storms, rarely show the optical effects produced by very small ice embryos.)

THE CHALLENGE

Thus, I suggest that a challenging problem that should be tackled by those weather engineers concerned about the management of clouds and weather is the development of methods to completely (or nearly) eliminate the formation of cirrus streamers produced by convective clouds. Such an accomplishment would be so dramatic and so effective in the production of local precipitation, it is unlikely there would be any question about whether or not the

cloud seeding in those areas was effective. With efficient cloud seeding which produces extremely small ice embryos, there should be dramatic optical effects if any cirrus areas are formed. This would provide a secondary indication that cloud seeding was involved in the particular weather development.

During a flight from Albany, New York, to San Francisco on December 9, 1972, our flight route via Chicago, Sioux Falls, Rapid City and Reno passed over nothing but middle level ice crystals. In most areas there were no optical effects of any kind, indicating that most of the cirrus and middle level ice crystal clouds were produced by ice nuclei which were acting by heterogeneous nucleation resulting from either inadvertant or glaciation effects. There were far too many crystals to have been produced by the concentration of ice nuclei commonly observed in "clean" air. Little if any precipitation was reaching the ground.

Thus, I feel confident that, if by optimum seeding of convective clouds on a routine basis one could effectively eliminate the development of cirrus clouds, there would no longer be a question as to whether or not cloud seeding "works"!

- - - - -

REFERENCES

(1) Schaefer, V. J., Journal of Weather Modification, Vol. 4, No. 1, 1972.

(2) Langmuir, I., "Cause and Effect Versus Probability in Shower Production," Vol. 11, No.215, Collected Works of Irving Langmuir, Pergamon Press: New York, 1960.

(3) Schaefer, V. J., Annual Reports Yellowstone Field Research Expeditions, 1960-1970, Atmospheric Sciences Research Center, SUNYA, Albany, New York.

(4) Schaefer, V. J., Final Report: Project Cirrus, Part 1, "Laboratory, Field and Flight Experiments," Contract No. DA36-039-SC-15345, GE Research Lab. Report No. RL785, March 1953.

(5) Schaefer, V. J., "Serendipity and the Development of Experimental Meteorology," Journal of Irrigation and Drainage Division, Proceedings ASCE 86 IRI 1-16 (1960).

(6) Schaefer, V. J., "Ice Crystals Formed Spontaneously by the Rapid Expansion of Moist Air," Journ. Col. Science, 9, 2 (1954).

(7) Langmuir, I., "Studies of Tropical Clouds," Vol. 11, No. 218, Collected Works of Irving Langmuir, Pergamon Press: New York, 1960.

(8) Langmuir, I., "The Production of Rain by a Chain Reaction in Cumulus Clouds at Temperatures above Freezing," Journal of Meteorology, 5, (175: 1948).

(9) Schaefer, V. J., "Ice Nuclei from Automobile Exhaust and Iodine Vapor," Science 154, 1555 (1966).

(10) Schaefer, V. J., "Cloud Exploration over Africa," Trans. New York Academy of Science, Sec. Ocean and Meteorology, 20, 535 (1958).

(11) Schaefer, V. J., and R. J. Cheng, "The Production of Ice Crystal Fragments by Sublimation and Electrification," J. de Recherches Atmospheriques, 5, 5, (1971).

- - - - -

THE SOUTH DAKOTA WEATHER MODIFICATION PROGRAM[a]

By Merlin C. Williams, Director

South Dakota Weather Control Commission
Pierre, South Dakota

I INTRODUCTION

Activities by state planners, interested private groups and legislators in 1970 led to legislative action in March 1971 to establish a statewide program of weather modification in South Dakota. This program is intended to provide an economic benefit to the people of the state through application of existing knowledge to increase rainfall and decrease hail by cloud seeding. In addition, the legislative action recognized the need to enhance knowledge in the field to improve the capability.

The South Dakota Weather Control Commission (WCC) is charged by law with the responsibility for weather modification activities in this state including the development of the statewide program. The Commission was established in 1953 when the basic law, South Dakota Compiled Law (SDCL) 38-9, concerning weather modification was passed. The Commission is composed of ten representatives, seven of whom are appointed by the Governor and three ex officio members representing the Department of Agriculture, the Water Resources Commission and the College of Agriculture of South Dakota State University. Through periodic meetings, the Commission provides general policy and oversight for the functions set forth by the law.

The detailed work of the Commission is conducted by the office of the Director. This office was established as a result of the amendment to SDCL 38-9 by the 1971 legislature. In September 1971, the Director's office began the task of designing, organizing and initiating the statewide program. This activity represented one of the four functions assigned to the Commission by the Law. These functions also include interstate and federal cooperation, special studies and regulation of all weather modification activities in the state through both licensing and monitoring.

---

a Presented at ASCE National Meeting on Water Resources Engineering, January 29 - February 2, 1973, at Washington, D.C.

This paper describes the activities of the Weather Control Commission in the design, organization and initiation of the statewide program. Cloud seeding activities during the first season of operation will be summarized, and program effectiveness will be described. It must be recognized that insufficient data can be obtained from a single year's operation to supply statistical significance to the results; therefore, no attempt will be made to indicate the effects of seeding.

II BACKGROUND

Private associations of farmers, ranchers and businessmen have been formed to sponsor weather modification in specific areas of the state since the early 1950's. Funding for these activities were provided by voluntary contributions. At one point in the mid 1950's, operations by a private contractor involved seeding with ground generators in an attempt to affect as much as 60% of the state. Relatively few areas of the state have not been the target of seeding attempts at one time or another.

Passage of enabling legislation in 1963 provided for more organized funding of weather modification through county tax structure. Various long term, county supported projects were developed in both the eastern and western part of the state. Examples of such programs are to be found in the western and northwestern grasslands areas and the northeastern crop area. Numerous shorter term projects were also developed on this basis in the south central and southeastern crop areas. Some measure of the degree to which such activities are supported can be obtained from the fact that county funding for weather modification throughout the state has averaged nearly $100,000 for the past ten years (1).

Results of these projects were not always documented. Funding limitations did not permit evaluation activities of a significant nature. In fact, funding limitations for projects sponsored by individual counties did not permit adequate operations in many cases. Routine evaluations of the activities based on comparisons of variations from long term normals for target and control areas were made by members of the WCC. Persistent indications of increases achieved by the cloud seeding were obtained from these evaluations. Those Commission efforts led to the support of a more formal evaluation of the locally sponsored efforts by the Institute of Atmospheric Sciences (IAS), South Dakota School of Mines and Technology, during the summer of 1971. This evaluation, which was funded under a contract with the WCC, provided strong indications that increases of 7% to 48% were being achieved in four different projects (3).

While it is recognized that these evaluations do not provide conclusive evidence for cloud seeding effects, they do represent a considerable body of qualitative evidence favorable to the seeding. This information together with research results was considered sufficient supporting evidence to warrant development of the applied, statewide program.

Results of research activities serve as a basis for portions of the program design. The most pertinent results are those obtained by projects in South Dakota. Specifically, concentrated experimentation has been underway by the IAS since 1963. This activity has been under the sponsorship of federal agencies such as the Bureau of Reclamation, National Science Foundation and National Oceanic and Atmospheric Administration. The research has involved both individual cloud experiments and areal testing. Through the use of scientific design and sophisticated techniques, these efforts have led to results which provide a stepwise program development. In 1969 a pilot project was developed to test the research results over large areas in North Dakota. Subsequent results made it possible for the IAS staff to make the summary statement in November 1971: "However, the overall result of a project based on the present state of the art of cloud seeding and lasting for a season or more should be an increase in total rainfall at the ground" (6). This conclusion was reinforced by the results of the evaluation of commercial seeding activities during the summer of 1971 (3).

South Dakota results are reinforced by results from other parts of the country and the world. Hail suppression activities in four southwestern counties of North Dakota indicate 30% to 60% decrease in hail (4). A cumulus experiment in California conducted during the summer months of 1966, 1967, and 1968 provided results indicating significant increases in runoff resulting from cloud seeding (18). Research on summer systems in Arizona sponsored by the Bureau of Reclamation between 1965 and 1969 provided support for increases resulting from seeding (15). Experiments in Florida by National Oceanic and Atmospheric Administration researchers provides strong evidence for increased precipitation from seeded convective cells (19). Results of seeding experiments in Australia have led to application of the technology for many years (2). Carefully conducted experiments in Israel between 1961 and 1967 led to development of an operational program in 1971 (9). Activities in Kenya since 1967 provide evidence of significant reduction in hail (as much as 60%) with corresponding increases in crop production (tea) (10). Reports of hail suppression activities in Russia include statements of ability to stop 70% to 85% of the hail for clouds treated by firing silver iodide bearing artillery shells into the cloud. (17).

III BASIS

The physical conditions associated with weather in South Dakota are characterized by a continental climate with cold winters, warm to hot summers, light moisture in the winter and moderate moisture in the summers. The climate is generally limiting or marginal for most crops in terms of both precipitation and growing season. Winter weather patterns are associated with cold, northerly flow from large, high pressure systems moving into the state from the north or northwest. Warm or hot summer air results from southerly flow which is interspersed with humid conditions when this air originates over the Gulf of Mexico. The entire state is characterized by frequent changes caused by cold fronts and associated low pressure areas moving across the state (5).

The maximum precipitation occurs during the growing season months. This precipitation varies from 18 inches in the southeast to 10 inches in the northwest, and results predominantly from convective activity with no major orographic influences except in the Black Hills region. Some measure of the degree of convective activity can be obtained from the fact that thunderstorms occur on an average of 40 to 45 days at any one location in the state.

Average increases of 15% to 20% as deemed possible by the research efforts at IAS (14) would provide an additional one to two inches of precipitation during the growing season. Hail may be expected in most parts of the state an average of two to three times a year. Hail losses are estimated to average $30,000,000 per year (13).

The potential for benefits from weather modification is variable for the activity being conducted. Variations in effect are also noted for different crop types. Preliminary estimates of the benefits to be achieved by an average increase of growing season precipitation of one inch would provide a benefit cost ratio of between 10 and 30 to one (14) through increased crop production. The additional benefit achieved by a 30% to 50% reduction in hail would increase the benefit to cost ratio significantly. In addition, these preliminary estimates do not specifically include benefits to urban areas. Reduction of hail damage and increased water supplies for cities and towns provides an additional significant benefit that is difficult to estimate at this time.

Considerably more detailed studies of benefits are underway by a research team of the College of Agriculture at South Dakota State University. Preliminary estimates have been made of the benefits to be derived from an average increase of one inch of rainfall during the growing season. An example of their findings can be obtained from consideration of wheat production where results indicate increases of one to nine bushels per acre depending on type, location and distribution of rainfall (7). Continuing studies of a broad range of economic considerations are underway not only by SDSU, but by surrounding Northern Great Plains states as well (8) (11).

Additional studies (11) and consultation with farm groups have identified another source of potential benefits in the form of increased preseason moisture. The effect of preseason moisture varies with crop type, but appears to be most important to forage and small grains. Additional investigation may well lead to the development of programs to provide seeding for periods other than the growing season.

Social concerns in the state are associated with agricultural activities since the economy of South Dakota is largely dependent on this industry. Approximately 70% of the state's economy is derived from agriculture and agriculture related activities (16). The general trend in farming operations in the last 30 years has been toward increasing mechanization and larger farms. This action has resulted in part from relatively constant prices for farm products while production costs increased. The overall effect of these factors is a resulting out-migration of population in the state. This factor is particularly significant in younger age groups, and results in a general economic and social problem for the state. It is generally accepted that stabilization of the agricultural economy will serve to reduce the social problem, but probably not eliminate it.

An average increase in precipitation of one to two inches of precipitation is generally recognized as a means of improving crop production; and, thereby contributing to stabilization. Opinion surveys indicate that 60% to 80% of the people accept weather modification as a tool to be used for this purpose, and feel that it can produce the beneficial effects proposed (12). A majority of the people are willing to spend their local and state tax money to support a weather modification program. Legislative approval of both the concept and funding of the program has been provided by the same margins.

The legal aspects of weather modification have been considered on an individual state basis. In this manner, consideration of local conditions

and needs has been included in the legal policy of the states. South Dakota claims sovereign right to the use of all water over its boundaries for the benefit of its residents. The law (SDCL 38-9) also provides a general recognition of weather modification as a state function entered into to provide for the general welfare of the public. It further recognizes the state of the art as being capable of producing beneficial changes under certain defined conditions.

The financial support for the program is broadly based throughout various levels of government. State support for the statewide activities is derived from general fund appropriations. The initial state appropriation amounted to $100,000, and was provided by the 1971 legislature for FY 1972 to design, organize and initiate the program. This action was followed by an appropriation of $250,000 for operations in FY 1973. Administrative funds for the conduct of Commission activities were provided under a separate budget appropriation in each case.

Authority for county support of weather modification is provided by SDCL 10-12-18. This law provides that counties may levy a maximum of one mill tax on assess property valuation for this purpose. The authority to levy and commit funds under this law rests solely with the county commissioners in each case however, in actual practice it is normally done on the advice of groups in the county. On occasion, the county commissioners have requested that approval to proceed with a program will be obtained by a vote of the people or a poll be taken to determine the wishes of the people.

Funding of weather modification activities by federal agencies has been limited to research either by administrative policy or Congressional directive. Thus, funds for support of the operational aspects of the statewide effort are not available; however, cooperative programs for the support of related evaluation and research activities have been developed. The Bureau of Reclamation participation in the program takes the form of funding support in the amount of $52,000 for a 15 month period to conduct research and special evaluation studies. This organization also supplies special services for operational testing. The National Oceanic and Atmospheric Administration is also providing support in the form of services and related research.

IV PROGRAM DESIGN AND ORGANIZATION

Initial investigation indicated that the technical design and organization would be inextricably bound together. Considerations of funding, equipment limitations, personnel availability and other technical features would determine the most effective type of organizational structure. Conversely, existing governmental and private characteristics would effect the technical considerations from the standpoint of location, areas covered and decision-making.

Administratively there was a need to have local involvement in decisions regarding cloud seeding activities by those people most affected by the out-

come. After consideration of a number of possibilities it became evident that a local-state cooperative effort was desirable. Examination of governmental structure indicated that county government was the most suitable for local representation. Reasons for this choice included such factors as, (1) county commissions represent an existing governmental structure, (2) they are familiar with local conditions and desires and, (3) they represent the smallest level of government that could provide effective decision-making.

The decision making proposed for the administrative aspect of the program was of two types. First, a decision to participate in a cooperative effort was required. Recognizing dissimilar local needs and desires, this decision was made voluntary. Secondly, decisions on the degree and type of activity needed to be made on the basis of local conditions. Thus, the local administrative structure was required to establish beginning and ending dates and provide recommendations for suspension or termination of activities when adverse effects (such as production of additional rainfall when above normal amounts affected farm operations) were prevalent.

A local-state cooperative feature was also desirable from the standpoint of funding. Such an arrangement would not only provide increased operational capability through a larger budget, but would provide a measure of the need and interest by local groups. Here again, county government was the most logical choice for local-state cooperative efforts. Their authority to tax to support weather modification provided the means for local level support.

After examination of various factors, a cost-share concept was developed wherein the counties provide 25% and the state 75% of the costs. Considerations involved in this concept included the relative role of agriculture in the overall state economy and the ability of counties to raise funds under the one mill limitation The latter consideration is significant for large counties with major portions of their area represented by non-taxable federal, state or Indian land. This factor has resulted in an inability of several counties to participate despite the unequal cost-sharing ratio.

Physical characteristics were also considered in the program organization. Climatic and soil zones were investigated to provide definition of homogeneous cropping zones. Use of such zones to organize areas of activity would provide the ability to make uniform seeding decisions. This point was quite important in view of the variation in precipitation, and, hence, crop patterns across the state.

In addition, consideration was given to the capabilities of the equipment currently available. Radar and aircraft capabilities provided the primary limitations on the size of the areas considered. Available radar could effectively cover a circle approximately 100 miles in diameter. Light aircraft of the type proposed could also be expected to cover an area approximately 100 miles in diameter without excessive loss in transport time. Minimum equipment required to meet the technical design could provide coverage for areas larger than single counties, therefore, multicounty operation would be more efficient than single county efforts.

All of the above considerations led to the adoption of multicounty districts operated on the basis of cost-sharing. Each of the districts is designed to consist of the counties that fit within a 100 mile circle within the limitations imposed by straight line county boundaries. Local level administration of each district is provided by a coordinating committee composed of one representative of each participating county commission. Districts and their associated counties participating during 1972 are shown in Figure 1.

V OPERATIONS - 1972

State funding for the summer field activities was provided by the 1972 legislature in the form of a $250,000 appropriation. This amount was inadequate to meet the requests by counties representing three full districts and two partially formed districts. The decision was made to provide full scale funding to the two adjacent districts in the southeast portion of the state with supplemental support to on-going county programs in the western and northwestern part of the state rather than try to provide limited support over the entire area requesting. Representatives of the district in the north central part of the state agreed to develop the administrative organization, but forego field operations until 1973 when funds became available. District cost-share funds from participating counties resulted in a total budget of approximately $340,000 from both state and county sources.

Contracts with private operators for equipment and personnel were awarded in March in preparation for field activities during the period May 1 through August 31. Aircraft acquired under these contracts were of the turbocharged, light, twin-engine type, fully equipped for high altitude and instrument operations. Complete navigation equipment provided the capability for day or night, all weather flights to meet the proposed requirement for seeding operations at any time. Each of the three aircraft provided to each complete district was equipped with both acetone-silver iodide type generators with a capability of dispensing silver iodide at a rate of 150 to 300 grams per hour and pyrotechnic devices capable of dispensing 200 grams per minute. Thus, a wide range of capabilities was provided for two types of seeding materials to permit either rainfall increase or hail suppression activities. Aircraft safety was stressed throughout the contract specifications.

Equipment contracts also provided for radar equipment with multiple capabilities. One radar system was located in each complete district with the capability for both storm monitoring and aircraft tracking. Radar storm surveillance provided the capability to detect storm characteristics, determine hail potential, provide seeding direction and coordination and provide continuous recording of all radar information by time lapse photography. In addition, each radar system included standard observing instruments for measuring meteorological parameters.

The requirement for experienced personnel was stressed in both the radar and aircraft contracts. A fully qualified individual with an academic degree in meteorology and experience in radar and/or weather modification work was provided for each district. A radar operator was provided by sep-

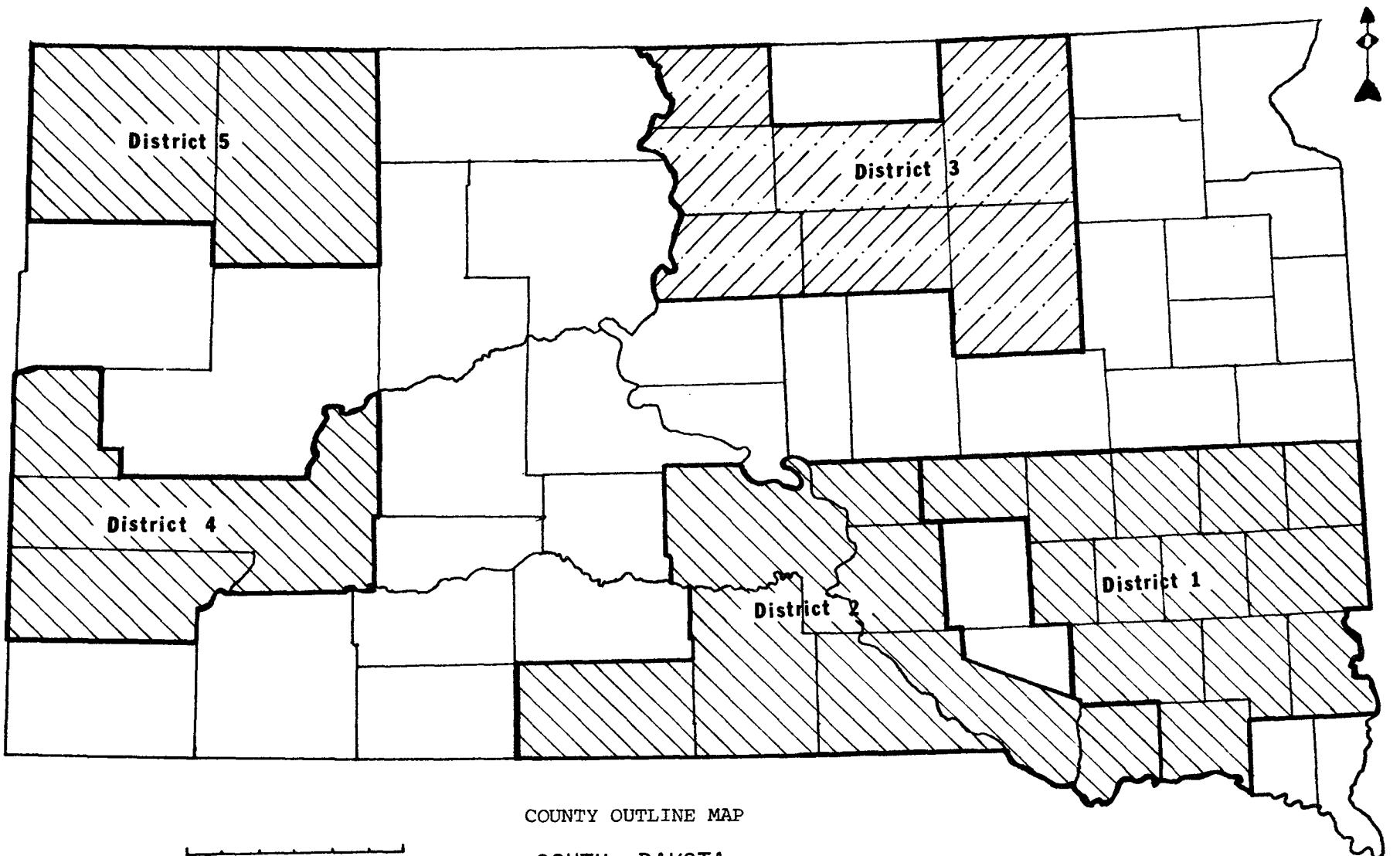


Figure 1. Counties Participating in 1972 Weather Modification Program

arate contract to assist the meteorologists at each site, and an electronic technician was provided to maintain and calibrate all radar systems. Three instrument rated, commercial pilots were provided for each site.

All equipment and personnel were ready to begin operations on May 1, however, natural events in the form of above normal rainfall resulting in difficulties to farming operations just prior to the starting date necessitated a delay. This circumstance provided a major test of the effectiveness of the organizational structure which utilized decision-making inputs from local coordinating committees. Normal operations required a full coordinating committee meeting once a month during operations with a telephone poll of each representative once a week to determine recommended operations. On May 1, all district representatives except one requested that nothing be done to aggravate a situation where excessive rainfall was hampering farm operations. (It should be noted that the representative from one county consistently requested full operation on the basis that the additional rainfall should be obtained whenever possible.) The suspension of rain enhacement activities extended throughout most of May and June, and periodic suspension of rain enhancement activities continued throughout most of the summer.

Crop development by mid-May had reached a stage where the occurrence of hail would cause damage. Accordingly, the Coordinating Committees were consulted regarding the advisability of initiating hail suppression at any time a clear cut indication of hail potential was identified. This action represented a departure from the original plan, and was made possible only by the flexibility provided by the local-state cooperative organization.

The results of this type of decision-making can be seen from a comparison of potential operations versus actual operations given in Figure 2. The potential operations represent estimates by the district meteorologist of the total number of aircraft seeding hours that could have been conducted for the weather systems that actually occurred. It should be noted that as the season progressed the potential opportunities decreased and the ratio of seeded to potential hours increased. Table 1 presents a summary of seeded days during the season.

Evaluation of rainfall is not expected to produce significant results due to the lack of seeded cases resulting from the frequent suspensions imposed on the effort. Some indications of effectiveness may be obtained in the two counties where seeding for rain enhancement was conducted for continuous periods in excess of one month. However, the overall conclusion must be that no valid evaluation of rainfall increases can be conducted for 1972.

Hail suppression evaluations are underway using hail insurance loss records. Historical hail loss records for the period 1928 to 1972 will be used to provide comparisons for evaluation. In addition, comparisons will be made between seeded and unseeded areas and times.

Qualitative evaluations of radar observations, seeding pilot observations and local observers reports are also underway. While this type of evaluation will not provide definitive proof of effectiveness, it does provide valuable background information for modification and improvement of future operations.

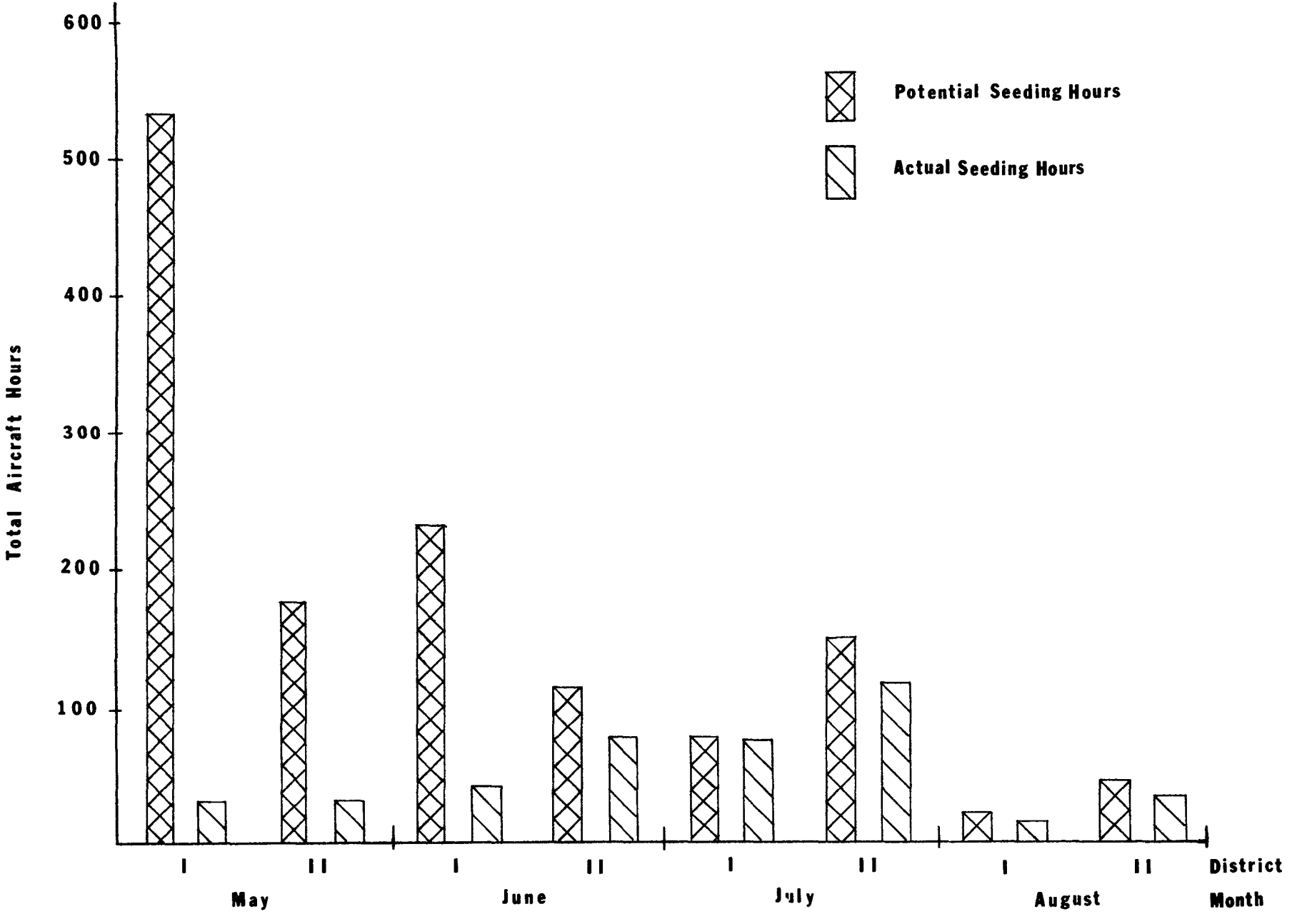


Figure 2. 1972 Operational Summary and Comparison

TABLE 1

SEEDING DAYS AND MISSIONS

(1972 Season)

DISTRICT I

	Rain Increase	Hail Suppression	Both
Days	10 (8)*	23 (19)	8 (6)
Missions	30	75	

DISTRICT II

	Rain Increase	Hail Suppression	Both
Days	12 (10)	16 (13)	13 (11)
Missions	42	75	

*( ) - % of total days

Various methods of evaluation are currently underway both by the staff of the WCC and under private contract. Data available for these evaluations consist of the following:

1. Radar cloud intensity and height measurements
2. Raingage observations from National Weather Service networks
3. WCC supplemental raingage observations obtained by cooperative observers
4. WCC hail occurrence observations obtained by cooperative observers
5. American Hail Actuarial Insurance Institute records
6. National Weather Service radar observations
7. WCC seeding operations logs

A post-program evaluation of costs indicates that the most meaningful estimate for varying size districts is a per unit basis. Using this method provides an average per acre cost of 3.2¢ for 1972 operations. On the basis of a 75% state-25% county basis, the costs are divided 2.4¢ per acre from state funds and 0.8¢ per acre from county funds.

VI FUTURE DEVELOPMENT

Organizational structure will remain essentially the same for 1973 with the exception of addition of as many new districts as funding permits. The district coordinating committees will continue to provide input to decision-making from the local level while the design, coordination, oversight and budgeting will be provided by the WCC staff. Cost sharing is also proposed to continue on the same basis.

No major changes are proposed for the technical design. Equipment, personnel and operational requirements for individual districts will be modified slightly on the basis of experience gained during the first summer, however, no major changes are anticipated. The emphasis and goals of the program will remain the same.

The major change in the program will be the overall size. A total of 26 counties participated in the program during 1972. In order to provide for effective planning and organization, all counties in the state were notified that requests for participation in 1973 needed to be submitted by September 10, 1972. A total of 42 counties responded representing an increase of almost twice as much area. This increase includes District 3 which was formed during 1972. Plans are currently underway to revise district boundaries and establish new districts to accomodate the additional counties shown in Figure 3. The number of counties and districts will be finally determined by the amount of the budget provided by legislative appropriation, since county funds are already obligated for this purpose. Accomodation of varying size areas is achievable by virtue of the flexibility inherent in the multi-county district organizational concept.

VII RELATED RESEARCH AND EVALUATION

Funding for the operational aspects of the program is derived solely from state and county sources. Limitations on funds provided to federal agencies restrict their use to research purposes which precludes federal participation in the operational phases of the program. However, conduct of certain research and evaluation in conjunction with the operations is not only desirable from the standpoint of enhancing knowledge and improving the operations, but required by the directive contained in SDCL 38-9. During the development of the program, cooperative relationships were developed with various federal agencies either directly or through other organizations to conduct special studies.

A contract with the Division of Atmospheric Water Resources Management of the Bureau of Reclamation provides for testing and development of certain

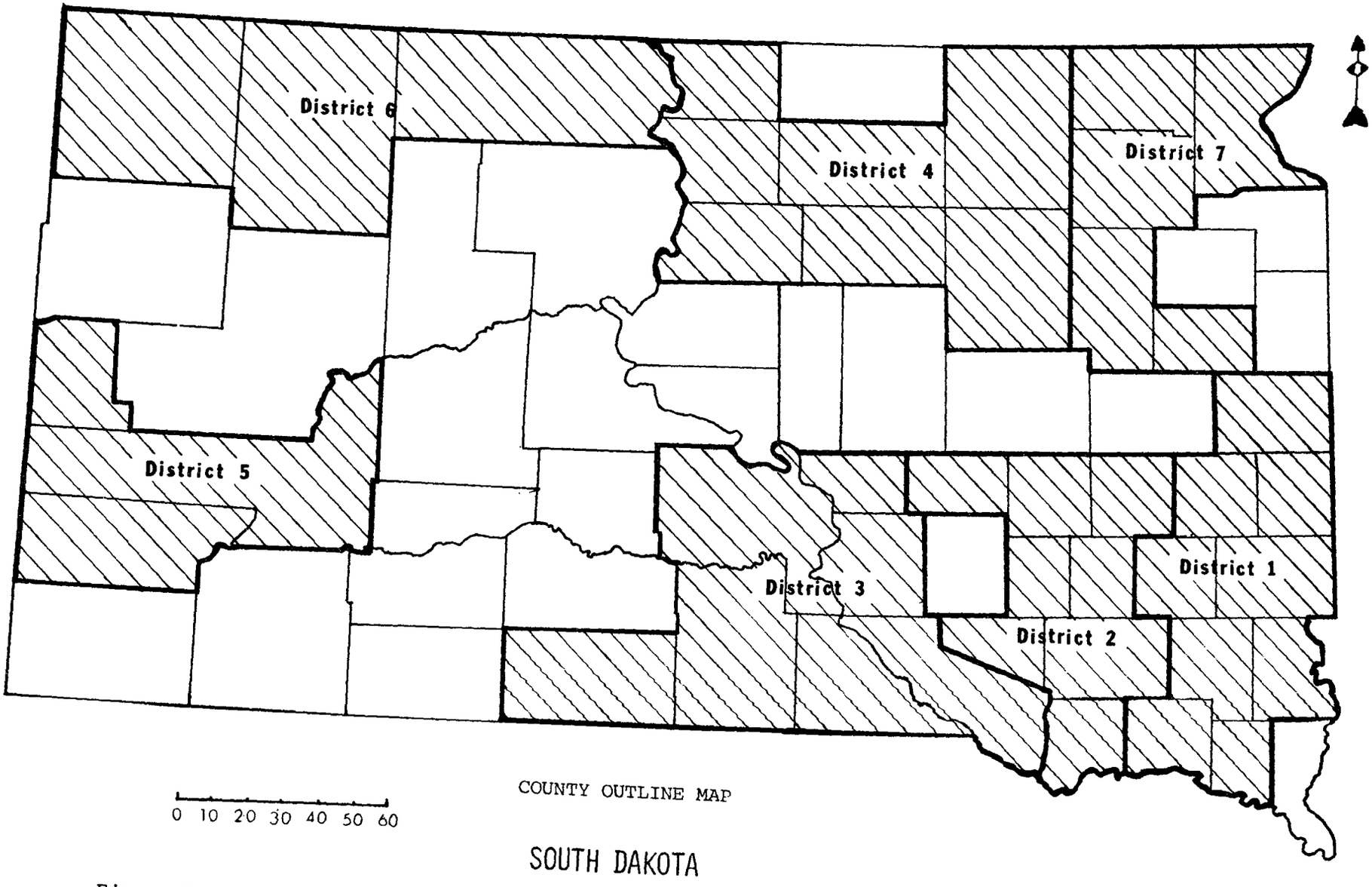


Figure 3. Proposed Weather Modification Districts - 1973

models and concepts in an effort to effect a technology transfer from research to operations. Testing during the summer seeding program of the effectiveness for operational purposes of the computer time-share system developed by that organization represented one phase of this project. A sub-contract arrangement with South Dakota State University provides for the development of sociological, economic and climatological models with which to evaluate the effectiveness of the seeding program. A second sub-contract with a private firm is designed to provide for development of conceptual models of cloud conditions with which to improve operational coordination and communication. Direct funding provides for establishment of a supplemental raingage network in seeded and unseeded areas in an effort to improve evaluation information. During the summer of 1972 a total of 175 such gages were operated by volunteer observers in the eastern half of the state.

Funding from the National Oceanic and Atmospheric Administration (NOAA) provides for both direct support and support to the IAS. Initiation of radiosonde operations at Huron, South Dakota on May 1, 1972 to coincide with initiation of the state program contributed significantly to the program. IAS efforts under NOAA funding consisted of efforts to develop techniques for evaluation of the field program through the use of the National Weather Service radar at Huron, South Dakota.

A third cooperative effort involves sociological studies conducted by the Institute of Behavioral Sciences, University of Colorado, under the sponsorship of the National Science Foundation. This program involves a study of attitudes of residents of the state toward the weather modification program. Testing is conducted before, during and after the seeding program takes place.

VIII REGIONAL PROGRAMS

The possibility of cooperative efforts with adjacent states is being investigated. Planners in both North Dakota and Nebraska have indicated interest in cooperative programs. Organized activities on the part of these states, however, will require legislative action to provide both the structure and funding for such efforts. The primary need at this point is the development of an organizational structure with enough flexibility to recognize the needs and requirements of the individual states.

Current action involves a proposal for joint projects in border counties. Negotiations for such a project have been completed with four counties in North Dakota. It is anticipated that activities in this project will be initiated in 1973. There are needs for additional projects of this nature in other areas of the state where border counties are involved.

In addition to joint operational efforts, a necessity exists to develop an interstate compacts system for operations along state boundaries where no seeding is taking place in the adjacent county. A distinct requirement exists to begin treatment of storm systems before they reach the upwind boundary of the target counties. For example, clouds moving southward from North Dakota to South Dakota should be treated 10 to 20 miles north of the state boundary in order to have an effect on areas in South Dakota imme-

diately adjacent to the boundary. Proper treatment should not cause an effect in areas of North Dakota. Establishment of a compact to permit such activities will require action by the Governors of the states involved, and must recognize differences in state laws regulating weather modification in each case.

Federal regional programs are under consideration in two areas of the Great Plains. The WCC will continue to cooperate in the development of these programs. In view of the fact that South Dakota has an operating program, the state may serve as a nucleus for such development. Steps are underway to provide information based on experience gained during the first year to other states establishing programs.

IX REGULATION

South Dakota has had a law to regulate and monitor all weather modification activities since 1953. This law requires both licensing and reporting of activities. Steps are now underway to modify and expand the existing law to keep pace with both the operational program and new developments in the field. The new law will provide for improvements in the structure and administration of the Commission. It will clarify and expand the functions of the Commission, and strengthen the regulatory authority of the State. To implement the new law a set of rules and regulations are being promulgated for administration of the provisions.

REFERENCES:

1. Atmospheric Water Resources Program, Project Skywater Proceedings: Skywater Conference VII, Division of Atmospheric Water Resources Management, Bureau of Reclamation, Denver, Colorado, March 1972.

2. Bowen, E. F., "Review of Current Australian Cloud Seeding Activities", Proceedings of the First National Conference on Weather Modification, April 28-May 1, 1968, American Meteorological Society, Boston, Mass.

3. Boyd, E. I., "South Dakota Cloud Seeding Evaluation, 1965-1971", Institute of Atmospheric Sciences, South Dakota School of Mines and Technology, Rapid City, South Dakota, November 1971.

4. Butchbaker, A. F., "Hailstorm Characteristics in the Vicinity of a Hail Suppression Project in Southwestern North Dakota during 1966, 1967 and 1968", Agricultural Engineering Department, North Dakota State University, Fargo, North Dakota, June 1969.

5. "Climate of South Dakota", Bulletin 582, November 1971, Agricultural Experiment Station, South Dakota State University, Brookings, South Dakota.

6. Dennis, A. S., "Effects of Cloud Seeding Upon Rainfall in South Dakota", Institute of Atmospheric Sciences, South Dakota School of Mines and Technology, Rapid City, South Dakota, November 1971.

7. "Effects of Additional Precipitation on Agricultural Production, the Environment, the Economy and Human Society in South Dakota" Annual report of Special Study Team of the Agricultural Experiment Station, South Dakota State University, Brookings, South Dakota, September 1972.

8. "Evaluation of the Effects of Added Rainfall During the Growing Season in North Dakota" Annual Report of Special Study Team, North Dakota State University, Fargo, North Dakota, September 1972.

9. Gabriel, K. R., "The Israeli Rainmaking Experiment 1961-67", Hebrew University, Jerusalem, May 1970.

10. Henderson, Thomas J., "Results from a Two-Year Operational Hail Suppression Program in Kenya, East Africa", Preprints, Second National Conference on Weather Modification, April 6-9, 1970, American Meteorological Society, Boston, Mass.

11. "Impacts of Induced Rainfall of the Great Plains of Montana - An Interim Report", Research Report 26, Montana Agricultural Experiment Station, Montana State University, Bozeman, Montana, July 1972.

12. Lanham, Orville, Jersome Rosonke and Karen Alickson, "A Sociological Analysis of Human Factors Related to Weather Modification", Department of Rural Sociology, South Dakota State University, Brookings, South Dakota (in preparation).

13. "A Precipitation Management Program for the Northern Plains", Report 71-12, Institute of Atmospheric Sciences, South Dakota School of Mines and Technology, Rapid City, South Dakota, August 1971.

14. Schleusener, R. A., and E. I. Boyd, "Physical and Economic Factors in the Preliminary Design of a Weather Modification Program for the State of South Dakota", Presented at Specialty Conference of American Society of Civil Engineering.

15. Smith, T. B. and A. I. Weinstein, "Arizona Weather Modification Research Program", Final report prepared for Bureau of Reclamation, Denver, Colorado, by Meteorology Research, Inc., Altadena, California, 1971.

16. "South Dakota Business Review", Business Research Bureau, School of Business, South Dakota University, Vermillion, South Dakota, Volume 31, No. 2, November 1972.

17. Sulakvelidze, G. K., N. Sh. Bibilashvili and V. F. Lapcheva, "Formation of Precipitation and Modification of Hail Processes", Israel Program for Scientific Translations, Jerusalem, 1967.

18. Williams, Merlin C., and Lehrman, Donald E., "Sierra Cumulus", Fresno State College Found., Atmospheric Water Resources Research, April 1970.

19. Woodley, William L., Joanne Simpson, Alan H. Miller, J.J. Fernandez-Partagos, William Riebsame, "Florida Cumulus Seeding for Drought Mitigation, April-May 1971", NOAA Technical Memorandum ERL OD-9, Environmental Research Lab, Office of the Director, Boulder, Colo., Nov. 1971.

OBSERVED UPDRAFTS AND HAIL INSIDE A THUNDERSTORM

W. R. Sand
R. A. Schleusener
D. J. Musil

Institute of Atmospheric Sciences
South Dakota School of Mines and Technology
Rapid City, South Dakota 57701

ABSTRACT

A North American T-28 aircraft has been highly modified and is being used to penetrate active mature thunderstorms. Observations during two penetrations made on 22 July 1972 are described. These show steady state storm structure and multiple regions of hail and icing.

1. INTRODUCTION

1.1 Description of the Aircraft

The Institute of Atmospheric Sciences at the South Dakota School of Mines and Technology has developed a research platform for the study of hail-producing thunderstorms. This platform is a highly modified North American T-28 aircraft. The aircraft is armored to withstand hailstones up to three inches in diameter without destructive damage. The T-28 has been fitted with numerous sensors and a recording system to permit acquisition of meteorological data during a thunderstorm penetration. A detailed description of the aircraft and data system can be found in Sand et al., 1972.

The T-28 was flown 70 hours (15 hours and 30 minutes of in cloud time) and made 83 cloud penetrations as part of the National Hail Research Experiment (NHRE) in 1972. This paper gives some results from two of these cloud penetrations.

1.2 Objectives

The National Hail Research Experiment is a project designed with two major general objectives. These are:

a) To gain an increased understanding, by observation and analysis, of all aspects of the cloud dynamics and microphysics governing the severe convective storms that produce damaging hailfall at the ground; and

b) Equipped with this increased knowledge, to develop, if possible, a practicable method for suppressing damaging hail (NHRE, 1972).

The mission of the T-28 is to sample the interior of the active thunderstorm concurrently with the scientific studies taking place at other places in and around the cloud. The scientific objectives of the T-28 project are to determine:

a) The updraft structure in regions of hail formation.

b) The composition of high radar reflectivity zones.

c) The ice-water budgets of hail-producing regions (Sand et al., 1972).

1.3 Flight Procedures

The T-28 penetrations were made between 16,000 and 24,000 ft MSL, in the region believed to be the "hail factory". The T-28 was vectored by radar to the area of highest radar reflectivity. Since a margin of safety was desired, a reflectivity limit was set above which penetrations would not be attempted. The radar reflectivity threshold for hail is reported to be about 50 dBz, (Chisholm, 1968; Dennis et al., 1971). It should be noted that this is a radar reflectivity threshold aloft for hail occurring at the ground. Therefore, a 55 dBz penetration limit was set to attempt to encounter only moderate hail until further experience is acquired.

Hail occurrence was recorded by a microphone behind the windshield which merely recorded the sound of hail striking the windshield. The relative concentration of hailstones was verified using this system. The pilot gave a subjective estimate of the size and frequency of hail encountered, the icing rate, and other general comments. This information was recorded on a voice recorder with periodic time references for later correlation with other recorded parameters. A 29-channel digital recorder was carried and various parameters were recorded each 0.63 seconds during a penetration.

The procedure used by the aircraft pilot during a penetration was to attempt to maintain a relatively constant airspeed and attitude and let the updrafts carry the aircraft up and down in the cloud. The vertical velocity of the aircraft was recorded from a Ball variometer and later corrected for power changes (manifold pressure) and airspeed fluctuations (both are recorded parameters) to give a corrected value which is believed to be within 10 percent of the actual updraft in the cloud.

2. OBSERVATIONS ON 22 JULY 1972

Data from a pair of penetrations are presented as an example of the updrafts and hail encountered during 2 of the 83 penetrations made during the 1972 season.

The penetration tracks and the corresponding 10-cm radar echoes at the approximate altitude of the T-28 are shown in Figures 1 and 2. The contoured slant range PPI traces presented only show reflectivity contours

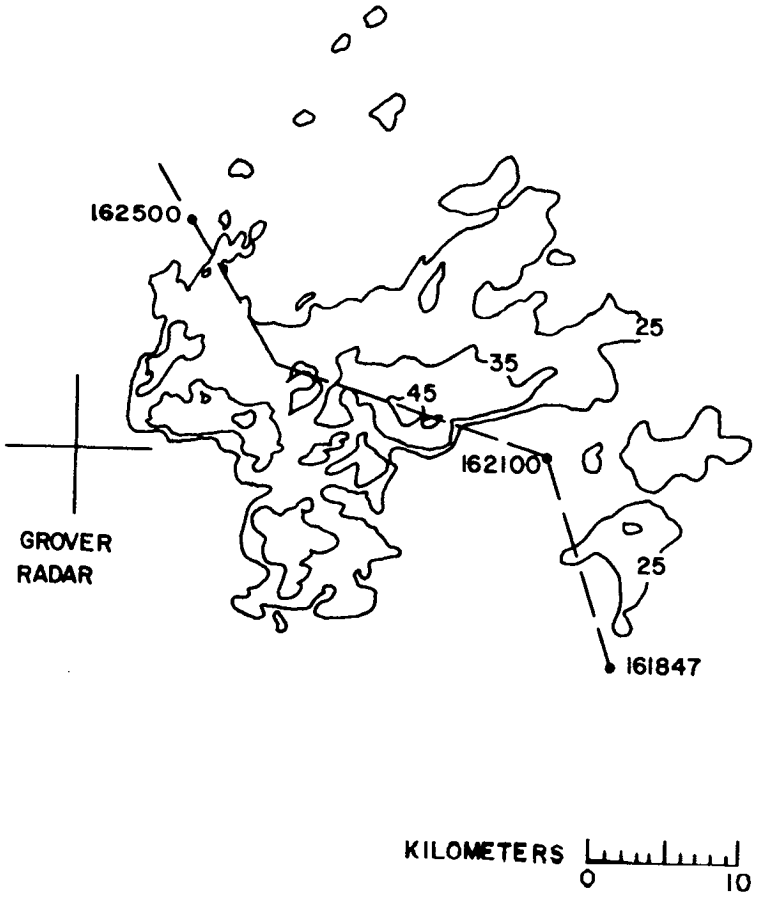


Fig. 1. Penetration 1. T-28 track with contoured slant range PPI at approximate altitude of penetration. The contours are labeled in dBz values.

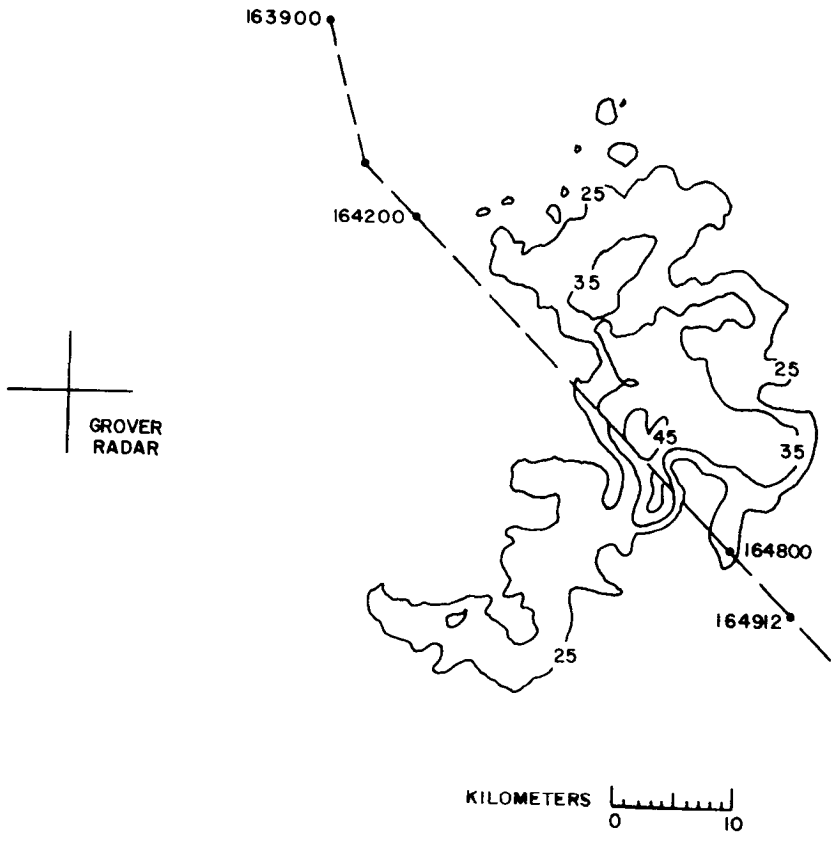


Fig. 2. Penetration 2. T-28 track with contoured slant range PPI at approximate altitude of penetration. The contours are labeled in dBz values.

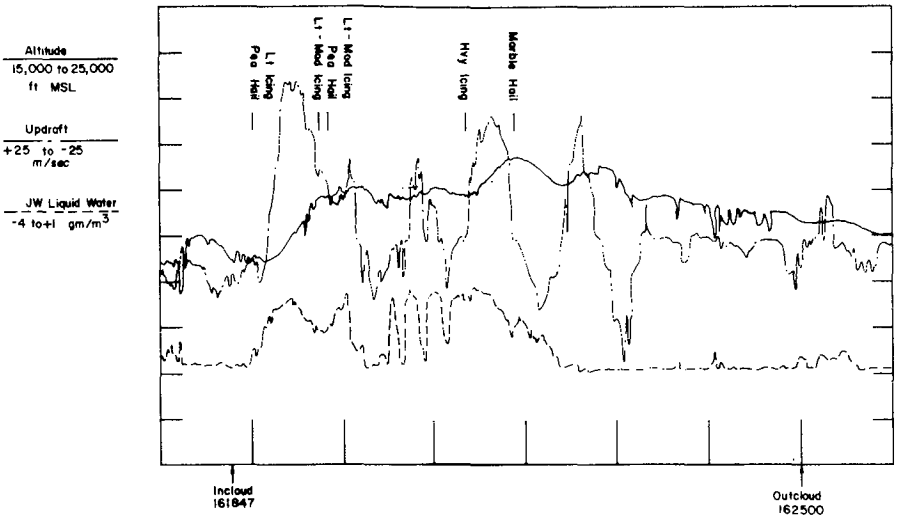


Figure 3.

Penetration 1. Analog traces of: (a) altitude; (b) updraft velocity; and (c) Johnson-Williams liquid water content.

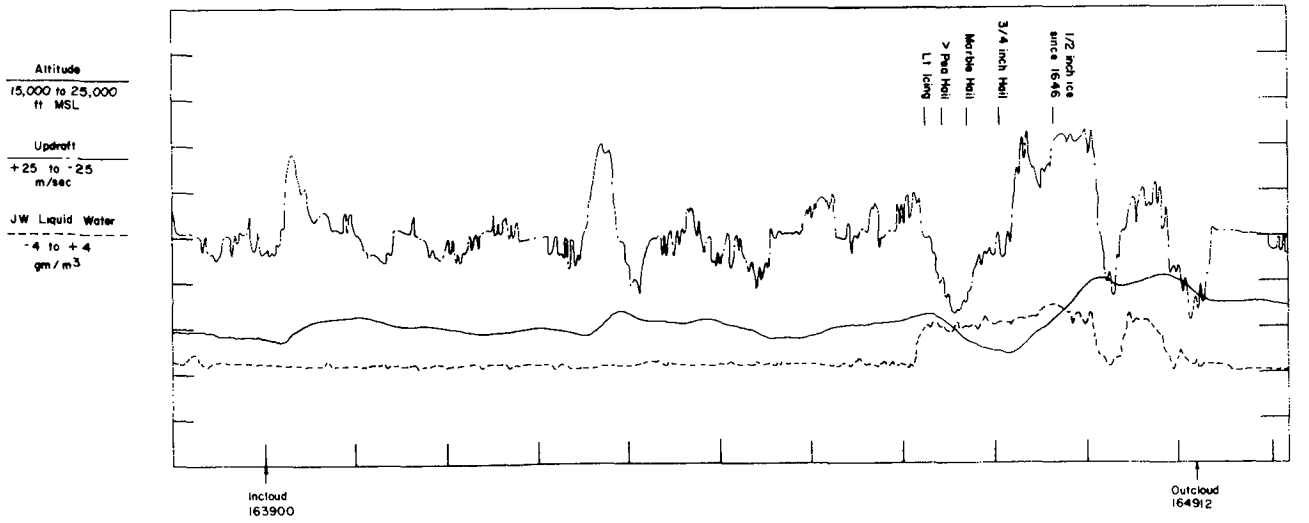


Figure 4.

Penetration 2. Analog traces of: (a) altitude; (b) updraft velocity; and (c) Johnson-Williams liquid water content.

to 45 dBz. The maximum reflectivity observed (noted in the radar log during either of these penetrations) was 58 dBz.

Analog plots of corrected updrafts, aircraft altitude, and Johnson-Williams liquid water content corresponding to the aircraft tracks in Figures 1 and 2 are shown in Figures 3 and 4. Hail encounters and relative hail sizes are annotated on Figures 3 and 4.

The liquid water content as given by the Johnson-Williams liquid water measuring device is not representative of the total liquid water present in the cloud since it senses only droplets less than 50 microns diameter. An instrument carried on the T-28 to measure total liquid water content, unfortunately malfunctioned during this flight. This device measured total liquid water contents as high as 28 gm m^{-3} during other penetrations in 1972 (Kyle and Sand, 1973).

An estimate of icing rates is included in Figures 3 and 4. These are subjective estimates made by the pilot at the time of the occurrence and are recorded on voice tape. Note that heavy icing rates often occur with hail encounters.

It is significant to note the occurrence of multiple updrafts and multiple hail shafts during the penetrations. The storm also showed a relatively steady state nature over the 30-minute time period between the start of the first penetration and the termination of the second penetration.

3. DISCUSSION OF THESE OBSERVATIONS

Although this is only a pair of penetrations on one storm there are some significant general observations which can be made. Further analysis will be accomplished pending acquisition of complete radar data and final computer reduction of the T-28 data.

The relative repeatability of multiple updrafts and hail occurrence from pass 1 to pass 2 shows the steady state nature of the storm penetrated.

Hail was encountered in regions of rapid substantial structural icing.

The fact that updrafts and hail were found in more than one place in the storm penetrated indicates that there was not a single core producing the hail but, in fact, multiple regions of hail growth. The hail encountered occurred consistently on the sides of the updrafts during these two penetrations implying that the hail grows along the edges of the updrafts.

At this time it is not readily apparent from these penetrations where the hail actually forms, but it appears that it is growing in areas along the edges of the updrafts. Thus the question remains open as to whether the regions of hail encountered are "hail factories" wherein the stones are formed and grow, or whether the regions of hail encountered should be considered as "hail assembly plants" wherein stones which originate in other locations grow to a larger size and finally fall out as a finished product.

Based on these two penetrations the observations have implications for field projects in hail suppression. Even though hailstorms may have steady state characteristics, the existence of multiple regions of hail formation within the cloud indicates that effective hail suppression will require successful "targeting" of seeding material into the multiple regions of hail formation and/or growth.

4. CONCLUSIONS

1) The cloud sampled had a steady state character and multiple updraft cores.

2) Hail was encountered in multiple areas in the cloud.

3) Hail was encountered along the edge of the updrafts.

4) Structural icing was experienced in regions where hail was encountered indicating the availability of supercooled moisture from which the hail could grow.

5) Successful hail suppression will require accurate targeting of seeding materials into the multiple regions of hail formation and/or growth.

ACKNOWLEDGEMENTS

The support of the National Science Foundation and the National Hail Research Experiment is gratefully acknowledged.

REFERENCES

Chisholm, A. J., 1968: Observations by 10-cm radar of an Alberta hailstorm in a sheared environment. Proc. 13th Radar Meteor. Conf., 82-87.

Dennis, A. S., P. L. Smith, Jr., E. I. Boyd, and D. J. Musil, 1971: Radar observations of hail in western Nebraska, Report 71-1, Institute of Atmospheric Sciences, South Dakota School of Mines and Technology, Rapid City, South Dakota, 42 pp.

Kyle, T. G., and W. R. Sand, 1973: Water content in convective storms. Submitted to Science for publication.

NHRE, 1972: National Hail Research Experiment Operations Plan 1972. National Center for Atmospheric Research, Boulder, Colorado.

Sand, W. R., R. A. Schleusener, and D. J. Musil, 1972: Final report of T-28 armored aircraft during the period 1 May 1971-1 May 1972. Institute of Atmospheric Sciences, South Dakota School of Mines and Technology, Rapid City, South Dakota, 55 pp.

HAIL SENSING AND SMALL-SCALE VARIABILITY OF WINDBLOWN HAIL

Stanley A. Changnon, Jr.

Illinois State Water Survey
Urbana, Illinois

INTRODUCTION

Time and space variability of hail, particularly of windblown hail, and the measurement of hail are key considerations relating to the proper evaluation of hail suppression efforts. Hailpads and other similar instruments have been used to measure and study hail in Colorado, Oregon, Illinois, Nebraska, South Dakota, and North Dakota, but these point measurements incorporate many obvious problems. These problems largely relate to the sampling questions (density of instruments per unit area, size of sensing area of the instrument, and the orientation-shape of sensing surface), and thus their adequacy for describing the actual hail over an area. The hailpads used have had varying sensing surface sizes, ranging from 36 in^2 (6 by 6 inch) to 144 in^2 (12 by 12 inch). Since all have horizontal sensing surfaces, they admittedly do not describe nor measure adequately windblown hailstones. Unfortunately, windblown hail has been shown to be quite significant in producing property damage (Changnon, 1962) and in producing damage to certain crops (Changnon, 1967).

This paper presents a discussion of the results of one of the measurement problems, sensing area size, and also includes results concerning the very small-scale variability of windblown hail.

A 6-year hail research program in Illinois has provided a large variety of data on surface hail measurements including the sampling density issue (Changnon, 1968) and point-area relationships (Changnon, 1971). Various recently completed studies on sensing area size and windblown hailstones have results with applications to those involved in hail suppression activities. A 2-year operation of a network of 232 hailpads, each with a sensing area of 1 ft^2 and located in a 800 mi^2 area in Central Illinois, has provided data to analyze for the differences in the hail energy values derived from small (36 in^2) and large (144 in^2) sensing area sizes. Secondly, a 6-year operation of a micro-network composed of 6 hailstool sites in a 0.01 mi^2 area has yielded interesting results on the frequency and small-scale variability of windblown hail.

EFFECT OF SENSING AREA SIZE

Sensing size is a potentially significant problem when hailpad energy values are used 1) to evaluate hail suppression activities and 2) to design various recording hailgages where cost and feasibility, both relating to the sensing area, are major limiting factors. One phase of the earlier surface hail studies in Illinois concerned a preliminary analysis of the effect of sensing area size on the measurement of hail energy (Changnon, 1969). This effort consisted of using data from 90 hailpads, each subdivided and then inter-compared.

To examine more fully the question of optimum size of a sensing area, data from 232 1-ft^2 hailpads in an Illinois network operated in 1971-72 were analyzed. For each of the 913 pads with hail, an energy value was determined for a) each of the four quarters (6 x 6 inch dimension) of the pad. These were each classed by position (NE, NW, SE, and SW), and subsequently the energy value for each was multiplied by 4 to obtain a value representative of a 144-in^2 area and thus ready for comparison with the values from entire 12 x 12-inch pad.

A listing of the frequency of the energy values from the entire pads and those derived from each quarter section (as adjusted by multiplying by 4) appears in Table 1, as sorted into 7 energy classes. All of the quarter pad energy values in the 0 to .0049 class, which included about 50% of their values, were zero (no energy), whereas none of the values from the entire pad were zero. This indicates that each of the 36 in^2 areas did not detect half of the hailfalls that occurred over the 144 in^2 areas. Admittedly, these are hailfalls of little consequence in relation to the production of crop or property damage. This tendency for the smaller area to sample a lower energy spectrum also is evident for energies in the range of .0050 to 0.1 ft lb/ft^2. Energy values in this range have been shown to be related to minor, less than 10%, wheat soybean losses (Changnon, 1971) and thus underestimates are of some concern. In the energy class ranging from .1 to .7, there are no essential differences between the small area and large area percentages. For the highest energy class, $\geq$ .7 ft lb/ft^2, the smaller areas all more frequently sampled high values with 5.1 to 6.5% of their values in this high energy class, whereas only 4.3% of the entire pad values fell in this class. Thus, the small areas sampled large energies 20 (5.1 to 4.3) to 50% (6.5 to 4.3) more often then did the large area.

TABLE 1

Comparison of Distributions of Energy Value for 1-ft^2 Hailpad and 0.25-ft^2 Hailpads

	Percent of all the energy values for a given pad, or section of pad, in a given energy class, ft lbs/ft^2						
	0 to .0049	.0050 to .0199	.0200- .0499	.0500 to .0999	.1 to .1999	.2 to .6999	$\geq$.7
Entire Pad	35.6	16.5	12.2	10.9	9.2	11.3	4.3
NE 1/4 of Pad	50.0	6.6	10.3	8.1	10.0	9.9	5.1
NE 1/4 of Pad	52.6	5.3	9.1	9.0	9.1	9.7	5.2
SE 1/4 of Pad	50.0	8.3	9.0	8.0	8.3	11.4	5.1
SW 1/4 of Pad	50.8	7.6	9.5	7.6	8.6	9.5	6.4

This tendancy for the small area to underestimate low energy values and to overestimate large energy values obviously relates to stone sizes and their spatial distributions. That is, when low energy values occurred only a few small stones fell, often resulting in no stones (and no energy) on some quarter/s of the large (144 in^2) pad. Conversely, when large energy values occurred, more stones fell but only a few large stones (that produced most of the energy) occurred. In this situation, 1 or 2 of the quarter areas normally experienced large stones and their resulting adjusted (multiplied by 4) energy estimates for estimating the energy for the 144-in^2 area were relatively larger than that for the entire pad.

SMALL-SCALE VARIABILITY OF WINDBLOWN HAILSTONES

INTRODUCTION

A very dense micro-network for studies of hail variability over short distances was operated during 1967-72 period in central Illinois. The network consisted of 7 hailstools installed at 6 sites in a rectangular area (Fig. 1) having an east-west dimension of 200 ft and a north-south dimension of 1200 ft (an area of 0.01 mi^2). Two of the hailstools were installed 6 ft apart and were used to investigate differences over a very short distance. One goal of the micro-network operation was to obtain information on the small-scale, much less than a mile, variations in windblown hail.

The sensing instrument used in this network, which is considered an improvement over the standard 'hailpad' with its horizontal sensing surface, is called a 'hailstool'. Its design allows for collection of data on windblown hailstones. The hailstool consist of 1) a 2-inch thick layer of poystyrene foam cut in a 12-inch diameter circle and glued to a circular piece of 1/4 inch thick hard fiberboard, and 2) a polystyrene cylinder 12-inch long and 6-inch in diameter that is centered and glued to the based of the upper sensing circular platform, to form a T-shaped device. This hailstool is supported on a 1-inch diameter rod driven into the ground or attached to a fence post. Commercial heavy-duty aluminum foil is wrapped around 1) the upper sensing platform, and 2) around the lower cylinder.

This particular construction and design allow several useful measurements of hailfall. The upper horizontal platform senses hailfall so that stone number, stone sizes, and energy can be calculated in the manner of hailpads used in various other areas. However, the large circular top and the smaller but long circular sensing area below the top platform allows measurement of vertical and azimuth angles of windblown hailstones. If stones fall vertically or within 13 degrees of the vertical, none hit the lower cylinder due to the overhang, but if they are windblown sufficiently to fall at angle - 14^o from the vertical, they impinge upon the foil wrapped around the lower cylinder and a limiting vertical angle can be assigned.

DATA

During the 6-year period of operation, 13 individual hailstreaks on 13 different days occurred hitting one or more of the 6 sites in this

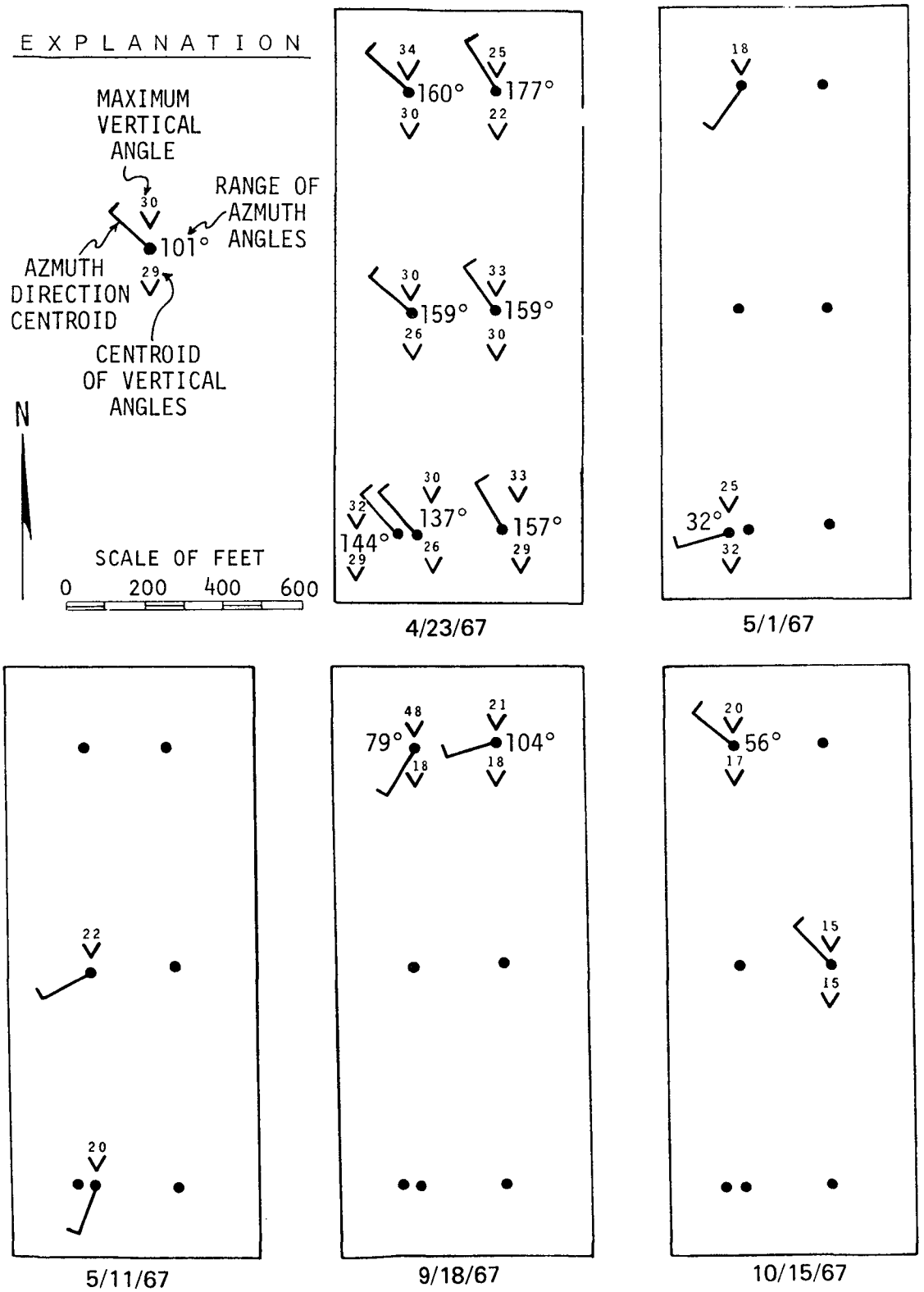


Figure 1. Maps of 10 hailstreaks with wind-blown stones showing hailpad data for the vertical (side) sensor

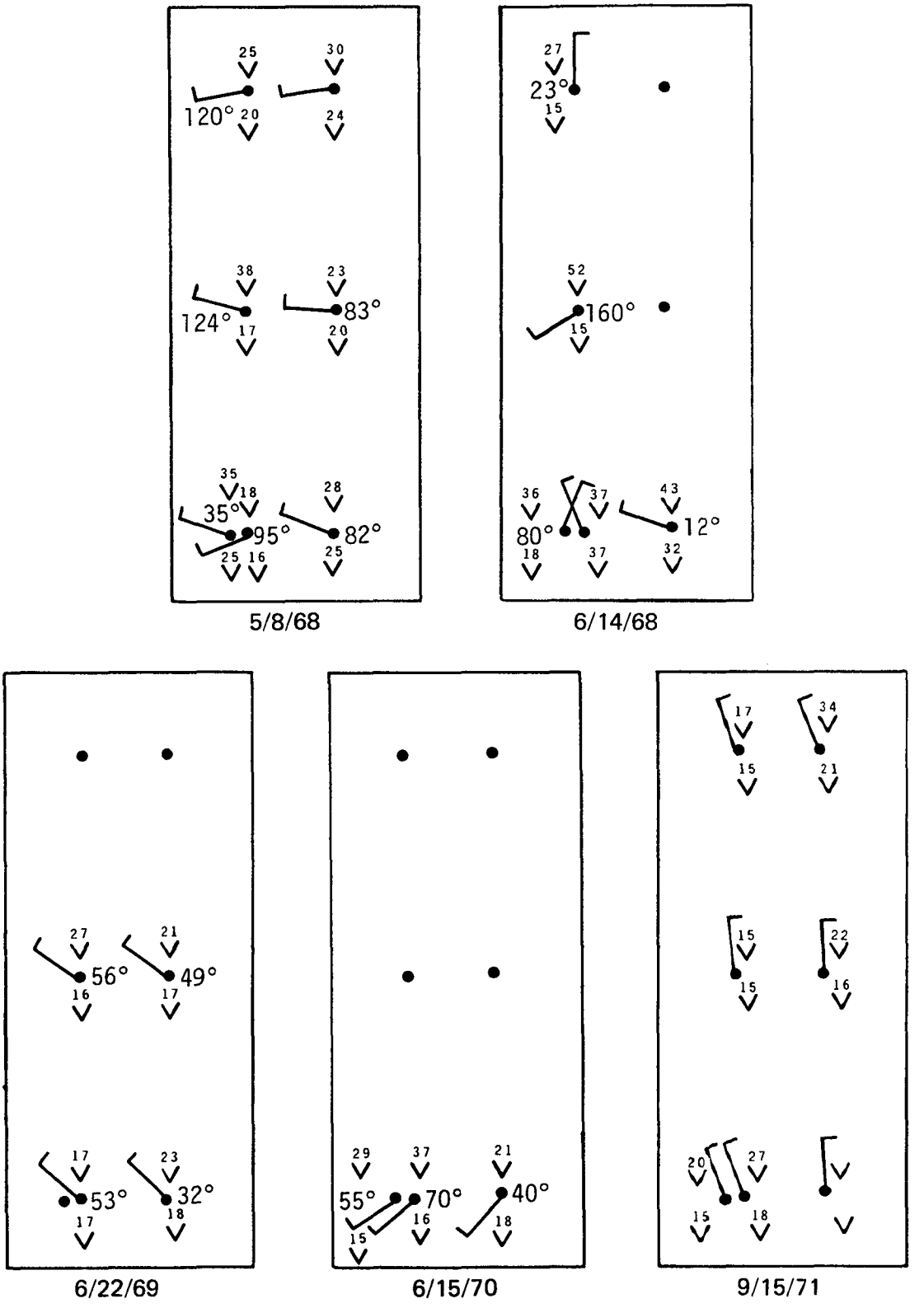


Figure 1 -- (Continued)

micro-network. Sites 1, 4, 5, and 6 had 10 hailfalls, and sites 2 and 3 each had 9. Ten of the 13 hailstreaks produced windblown hailstones at 1 or more hailstools. In 2 hailstreaks, windblown hail occurred at all 6 sites. Interestingly, none of the hailstreaks that affected the network were sufficiently narrow (less than 1200 feet) to have both edges defined. The patterns and data for the 10 hailstreaks with windblown hail are shown on Fig. 1.

In analyzing each hailstool, the number of hailstones on the upper (horizontal) sensing surface was counted including the number with diameters greater than 0.2 inch. The energy imparted also was calculated based on the stones on the upper sensing platform. If hailstones impinged on the lower, smaller cylinder, the azimuth angle information that was obtained included the extremes of the hailstone hits (for instance, from 200^{0} to 280^{0} may have been the spread on a side), and the centroid of all the hailstone azimuth values. The vertical angle information, as measured down from straight up, obtained included the maximum vertical angle measured, and the centroid of the vertical angles of all the stones on the side of the cylinder. Thus, there were 5 angular measurements made of the windblown hailstones. The number of windblown hailstones that hit the side of the cylinder was also recorded.

FREQUENCY OF HAILSTONES

With 13 hailstreaks and 7 hailstools, the possible number of hailstools with hailfalls was 91 (13 x 7), but the number with hailfalls on their horizontal surfaces (tops) was only 68. Their frequencies of hailstones, sorted into class intervals, are shown in Table 2. The average number of hailstones per hailstool top was 14, and the maximum number at a point was 81. The number of hailstools with 1 or more windblown hailstones was 41 (60% of all hailstools with hail on their top). The point (side) frequencies of windblown the hailstones is also shown in Table 2, sorted into class intervals. The average number on a side (given that 1 or more stones hit the side) was 8 (6 less than the top average), and the median value was 6 windblown hailstones. The greatest number to hit a side was 26 hailstones.

The relationship between top (vertically falling plus windblown stones) and side (windblown only) stone frequencies is revealed in Table 2. Four of the 41 hailstools with windblown hailstones had more stones on the sides than on the top surface. The average ratio of the hailstone top frequency to the side frequency, as based on the 41 stools with top and side stones, was 3.7. However, the sensing area of the top surface is 1.57 times greater than that of the side surface (assuming all stones came from one direction), making it reasonable to adjust the side frequency in order to obtain a meaningful comparison. Therefore, for each hailstool with windblown stones, their number was multiplied by 1.57 to get an estimate of a windblown total comparable to the top total. The average ratio of the top's stone frequency to the side "adjusted" frequency was 2.3. After the side area adjustments were made to the 41 values, only 10 had side frequencies equal to or greater than their top frequencies. The adjusted T/S ratios based on the adjusted ratios varied from 0.1 (10 times more on the side than top) to 10.0.

TABLE 2.

Relationship of Stone Frequencies of Hailstool Top Surfaces and Side Surfaces, 1967-72

Frequency for given numbers of stones on top surface	Frequency for given numbers of stones on side of hailstool							
	0	1-5	6-10	11-15	16-20	21-25	26-30	Total
1-5	19	5	4					28
6-10	3	3	1	1				8
11-15	1	1	3	1				6
16-20	1	2	2	3		1		9
21-25		2	1		1			4
26-30	1	1	2	1				5
31-35	1	1						2
36-40	1		1					2
41-50			1					1
51-60							1	1
61-70			1					1
71-80								0
81-90					1			1
	27	15	16	6	2	1	1	68

Since the windblown stones also impact on the top surface (and are counted with any non-windblown stones), the initial number of non-windblown stones that fell w-s = T - S_{adj}. The number of windblown ($\geq$ 14 degree vertical angle) stones was expressed as a percent of the total hailstones at each hailstool ($\frac{S_{adj}}{T}$), and the frequency distribu tion appears in Table 3. The median is 66 percent, and in 12 of the hailfalls, all stones (100%) were windblown.

TABLE 3

Percent of total hailstones at a point (hailstool) that were windblown, sorted into class intervals

Number of hailfalls for each percent class interval

1-10%	11-20%	21-30%	31-40%	41-50%	51-60%	61-70%	71-80%	81-90%	91-99%	100%
1	5	2	5	1	3	6	4	1	1	12

Directions of Windblown Stones

The azimuths (direction) of all windblown stones were determined at each of the 41 hailstools with 1 or more such stones. A centroid angle of all the stones was determined and the maximum angular of values was also measured, and these values appear in Fig. 1. Examination of the centroid arrows reveals a) a great in-streak variability, and b) great differences between hailstreaks.

The centroid azimuth angles were sorted into 20-degree class intervals and their frequencies appear in Table 4. The median of the 41 centroid values was 320 degrees, with individual centroid angles varying from 204° (see 11 May 1967, Fig. 1) to 20° (see 14 June 1968, Fig. 1).

TABLE 4

Distribution of azimuth angle centroids of each hailstool with windblown stones

Number per angular class interval

201°-220°	221°-240°	241°-260°	261°-280°	281°-300°	301°-320°	321°-340°	341°-360°	0°-20°	Total
3	4	5	5	3	7	4	9	1	41

The in-storm variability for the 10 hailstreaks with windblown stones is revealed further in Table 5. The median of these values is 30°. When all sites had windblown stones, the smallest difference was 15° and the greatest was 34°. The average angular spread in the stones was 85°, and it varied from a low of 5 degrees on 1 hailstool (site 3 on 15 June 1970) to a high of 177 degrees on site 2 on 23 April 1967 (Fig. 1).

Examination of the centroid azimuth arrows on Fig. 1 for each of the 10 hailstreaks reveals directional consistency across the network in 5 hailstreaks (23 April 1967, 15 October 1967, 8 May 1968, 22 June 1969, and 15 June 1970). However, quite variable wind-related patterns are shown for the other 5 hailstreaks.

Vertical Angles of Windblown Hailstones

The vertical angles of all windblown hailstones were measured and then the centroid angle of all the stones and the maximum vertical angle were determined.

TABLE 5

Ranges (in degrees) in the centroid of azimuth angles on an individual hailstreak basis(1)

Hailstreak Date	Number of hailstools with windblown stones	Measured extremes of centroids for hailstreak	Maximum difference, degrees	Median Angle
4/23/67	7	300^{o}-334^{o}	34	325
5/ 1/67	2	235^{o}-263^{o}	28	249
5/11/67	2	204^{o}-247^{o}	43	226
9/18/67	2	205^{o}-250^{o}	45	228
10/15/67	2	308^{o}-315^{o}	7	312
5/ 8/68	7	250^{o}-281^{o}	31	270
6/14/68	5	241^{o}-020^{o}	140	350
6/22/69	4	300^{o}-311^{o}	11	305
6/15/70	7	345^{o}-360^{o}	15	355
9/ 5/71	3	220^{o}-241^{o}	21	235

(1) Based on 2 or more hailstools with windblown stones

Vertical angles were assigned based on an assumption that the hailstone fell just beyond the edge of the upper platform, and the angles so calculated must be considered a potential underestimate of the true vertical angle since the hailstone could have come at greater angle.

The centroid vertical angles, sorted into 10-degree classes beginning with 14 degree (the minimum possible angle formed by the hailstool dimensions), appear on Table 6. The average of these 41 centroid angles was 20 degrees (Table 7) with extremes of 15 to 32 degrees. The maximum vertical angles measured are also sorted into classes (Table 6), and their average was 28 degrees (Table 7) with extremes of 15 to 52 degrees.

Variations in both vertical angles determined between points on an individual hailstreak basis are shown on Fig. 1. These exhibit some variability, but the range of greatest differences between sites in a single hailstreak averaged to be only 6 degrees for the centroids and 38 degrees for maximum vertical angles sampled.

TABLE 6

Frequency distribution of vertical angles of windblown hailstones, 1967-72

Number of hailstool values per class interval of vertical angle

	14^{o}-20^{o}	21^{o}-28^{o}	29^{o}-35^{o}	36^{o}-42^{o}	43^{o}-49^{o}	50^{o}-56^{o}	Total
Centroid[1]	26	9	5	1	0	0	41
Maximum[2]	9	14	11	4	2	1	41

[1]Center of concentration of all stones

[2]Greatest vertical angle (up = 0^{o}) on each hailstool

TABLE 7

Averages and extremes for vertical angles of windblown hailstones

	Centroid angle, degrees	Maximum angle, degrees
Average	20	28
Maximum	32	52
Minimum	15	15

Comparison of Hailfall Measurements at Close Range

The data for the two hailstools located 6 ft apart, although based on only 13 possible incidents, allow for comparisons of differences in windblown hailfalls across a 6-foot distance. The differences noted can be attributed to natural small-scale variability and possibly to inadequacy in the sampling devices (size and/or shape). The number of samples were too small for correlation analysis, but a graphical representation of the results offers some interesting observations.

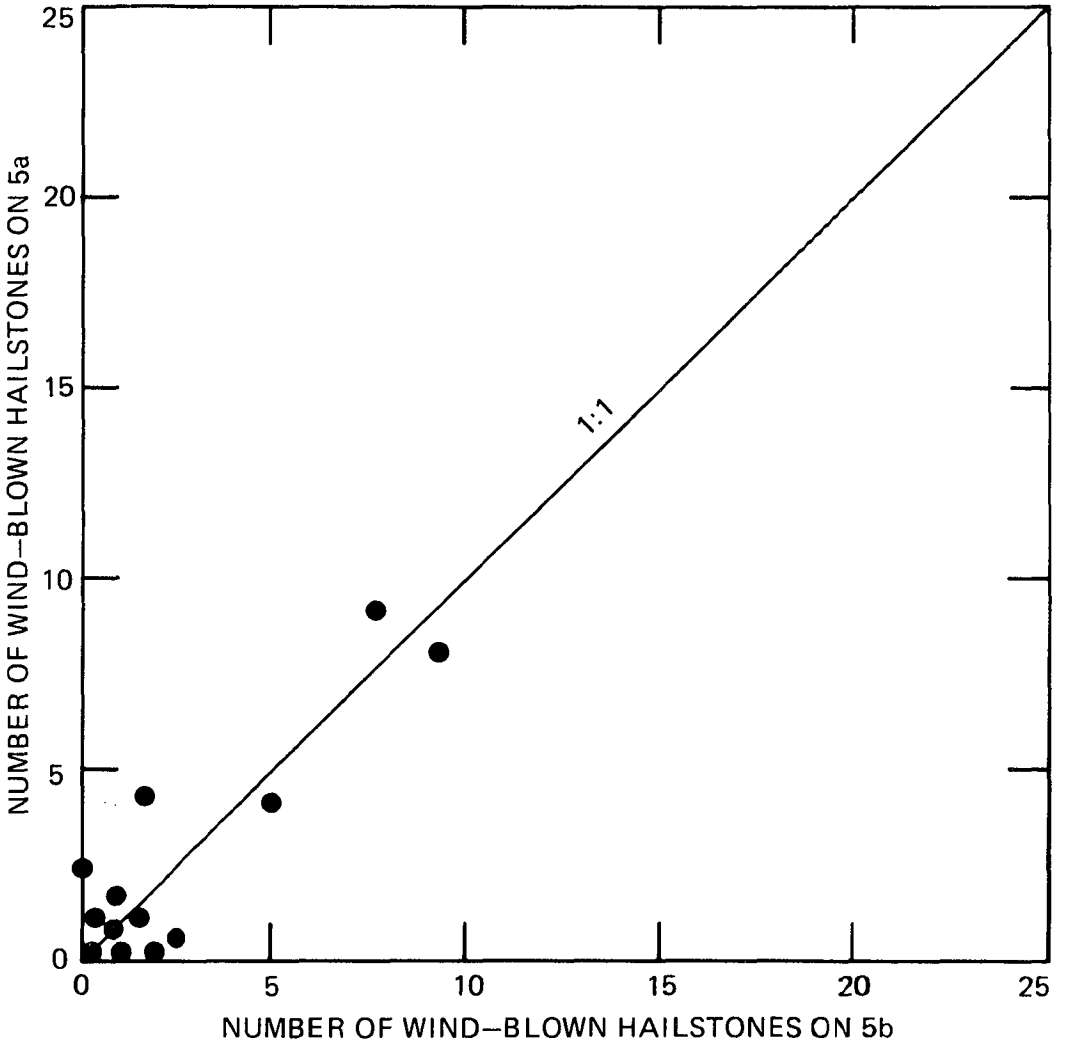


Figure 2. Comparison of wind-blown hailstone frequencies on hailstools six feet apart

Comparison of the frequency windblown stones, Figure 2, shows a moderately good relationship, but there were 3 hailstreaks that produced hailstones at only 1 of the 2 hailstools. Differences per streak in the centroids of their azimuth and vertical angles also were examined for the 5 streaks when both nearby hailstools have windblown stones. The 5 differences in azimuth angles were 0^0, 3^0, 5^0, 28^0, and 30^0 (an average difference of 13^0), and those for the vertical angles were 1^0, 2^0, 3^0, 9^0, and 19^0 (an average of 7^0). In general, the results indicate that there was very little difference between the two sites.

SUMMARY

If one assumes that the 144-in^2 sensing area provides the better estimate of hailfall energy, the Illinois results indicate that the smaller 36-in^2 sensing area misses 50% of very small hailfalls occurring in a square foot around it, underestimates the number of low energy values, correctly samples the number of moderate to high enery values, but overestimates (by 20 to 50%) the number of extremely large energy values. All of this difference results because of spatial distributions of hailstones found in the Illinois hailstorms. The relative similarity between the energy distribution for the small and large sensing areas for the energies above 0.1 ft lb/ft^2 (they ranged from 24 to 25% of the total energies for the entire pad and the 4 quarters) do suggest, however, that the size difference is not critical for the energy values of greatest significance.

The study of small-scale variations in windblown hailstones in a 0.01 mi^2 area was limited by a small sample of only 13 hailstreaks, and only 10 produced windblown hailstones at 1 or more sites. However, the data and results are useful in giving preliminary estimates of windblown hail characteristics.

Hailstones were windblown from many directions, ranging from SSW through W, NW, N and onto NNE. Their vertical angles also varied considerably, but most angles were less 40 degrees. Patterns of windblown stones (directions and vertical angles) were either relatively homogeneous across the small network, or were highly variable reflecting very localized differences in circulation. Windblown stones occurred 60% of the time when hail fell at a point; and when windblown hail fell, 66% of the hailstones were windblown.

- - - - -

REFERENCES

Changnon, S. A., 1962: Surface features of two interesting hailstorms. Nubila, 5, 74-86.

Changnon, S. A., 1967: Areal-temporal variations of hail intensity in Illinois. J. Appl. Meteoro., 6, 536-541.

Changnon, S. A., 1968: Effect of sampling density on areal extent of damaging hail. J. Appl. Meteoro., 7, 518-521.

Changnon, S. A., 1969: Hail evaluation techniques. Final Report NSF GA-482, Illinois State Water Survey, Urbana, 97 pp.

Changnon, S. A., 1971: Means of estimating areal hail-day frequencies. J. Wea. Mod., 3, 154-159.

- - - - -

PROJECT HAILSTOP: A REVIEW OF ACCOMPLISHMENTS TO DATE

Peter W. Summers

Research Council of Alberta
Edmonton, Alberta

1. PROJECT GOAL

Since direct crop losses due to hail in Alberta are estimated to average between $20 and $25 million annually (Summers and Wojtiw, 1971), the economic potential of an effective method of hail suppression, even if it can eliminate only a fraction of the damage, is self evident. Project Hailstop is designed to develop such a cloud seeding system within the framework of the Alberta Hail Studies project.*

2. PROJECT PHILOSOPHY AND DEVELOPMENT PLAN

The basic philosophy of Project Hailstop is shown in Figure 1, which gives a logical step-by-step plan for developing an operational hail suppression program.

2.1 Step 1

The first step was to make observations on hailstorms and develop radar and kinematic models of storm structure and mathematical models of the microphysics of hailstone growth. The Albert Hail Studies project was set up in 1956 with this as its initial goal. Substantial progress has been made, as indicated by Hitschfeld (1971) in a comprehensive review of the basic research carried out during the last 15 years, mainly by the Stormy Weather Group at McGill University.

2.2 Steps 2 and 3

Whilst knowledge of hailstorms is still far from complete, it had reached the point a few years ago where plausible hail suppression concepts could be formulated. Project Hailstop was thus conceived in late 1968 with ideas further developed in 1969 and then implemented in 1970. A new approach to seeding hailstorms was developed by the Research Council of Alberta with the technical assistance of the National Aeronautical Establishment (NAE).

---

*The Alberta Hail Studies (ALHAS) project is a cooperative investigation into all aspects of hailstorms which is sponsored by the Research Council of Alberta, the Atmospheric Environment Service and the National Research Council with scientific support supplied by the Stormy Weather Group of McGill University under contract to the Atmospheric Environment Service.

The seeding system was given a limited field trial in July 1970, on the basis of which improvements were made and the system given a fuller trial over a two month period in summer 1971.

2.3 Step 4

The Project is now at step 4, probably the most difficult, and is presently trying to assess whether physical effects have been produced on storms and whether hail size and/or intensity has been affected. Discussion of this work will form the main content of this paper. It will be preceded by a brief review of the seeding concept and the seeding system.

2.4 Step 5

Preliminary work on step 5 has begun, and can continue in parallel with step 4. Relationships between hail size or intensity (as measured by impact energy) and hail crop damage, developed by Summers and Wojtiw (1971), form a basis for determining whether any observed reductions in these hailfall parameters are beneficial to agriculture by reducing hail damage.

2.5 Steps 6 and 7

The sixth and seventh steps can only follow once a cause and effect relationship between cloud seeding and reduced hail damage has been firmly established. The work of Petersen (1972) provides a preliminary basis for the assessment of benefit/cost ratios but many factors other than strictly economic will have to be considered before hail suppression can be put on a full-scale operational basis in Alberta. The factors include legal, political, sociological and psychological, some of which are discussed by Petersen.

3. THE HAIL SUPPRESSION CONCEPT

Several hail suppression concepts have been proposed but only one is generally accepted as being realistic on the basis of current knowledge and seeding technology. The basic concept is to increase the number of hail embryos competing for the given water supply in the storm. Assuming the accretion process operates at high efficiency in the natural system, then if the number of embryos is increased by a factor of 100 or more, the hailstone diameters will be decreased by a factor of at least $\sqrt[3]{100}$ (i.e. 4.6). The hail reaching the ground will either be smaller and thereby cause less damage- Summers and Wojtiw (1971) show that hail less than grape size seldom causes significant damage - or will melt and reach the ground as rain. The most obvious way of accomplishing this is to increase the number of freezing nuclei in the storm system by the introduction of large numbers of artificial nuclei, usually silver iodide. However, the question of exactly when, where and how many nuclei are required to produce the optimum effect is still far from being resolved.

4. CHARACTERISTICS OF ALBERTA STORMS

4.1 Multicell Storms

A characteristic common to most Alberta storms is that they propagate to the right of the midtropospheric wind flow by means of new development occurring on their right-hand or southern flank. In the case of multicellular storms this development consists of surges of new activity which appear at intervals of between 5 and 15 min as one or more large cumulus towers rising rapidly and then merging with the parent storm. The first radar echo usually forms aloft at about 20,000 - 25,000 ft and then grows rapidly to form a new cell which can be followed as a distinct entity for between 15 and 40 min as it moves in the direction of the 500 mb wind through the storm complex. The life cycle of these cells is described in detail by Renick (1971b). The new cloud towers are the regions responsible for the production of the rain and hail which will reach the ground some 15 - 30 min later. Thus in order to apply the hail suppression concept it is required that these new developments be heavily seeded in order to increase the number of ice particles entering the storm system.

4.2 Supercell Storms

Although supercell storms occur less frequently than multicell storms - Marwitz (1972) estimates that each July in the ALHAS study area there are 3 days with severe multicell storms and 2 days with severe supercell storms - they do produce a substantial fraction of the annual hail damage. These storms often appear visually to be very similar to multicell storms, in as much as new cumulus towers are observed growing on the south or west side. However the radar structure appears to be more stable with a large weak echo region, assumed to be a large quasi-steady updraft by Chisholm (1970a), surrounded by a region of high reflectivity. Sometimes there is evidence of discrete radar cells moving through the storm system, but they are not nearly as well defined or as regular in their behavior as in the case of multicell storms. The relation of the new cumulus towers to the growth of large hail in the storm system is not clear, but it was decided that if the opportunity arose these towers would be seeded. However, it must be remembered that the hail suppression concept and seeding system were initially designed for multicell storms.

5. THE SEEDING SYSTEM

A wide variety of techniques have been used to deliver the seeding material into hailstorms (Summers et al., 1972), in several experiments at various places around the world. The most promising technique appears to be one whereby high concentrations of AgI are injected directly into a small cloud volume where the hail embryos are thought to originate. This technique was pioneered in the USSR by Sulakvelidze (1968) and Kartsivadze (1968) using anti-aircraft guns and ground-based rockets to deliver the AgI payload into a target zone precisely defined by its radar characteristics and temperature range. Alternative methods of accomplishing direct injection are being

investigated, including the use of airborne rockets in the US National Hail Research Experiment now being conducted in NE Colorado.

Rockets and shells are logistically difficult and pose safety problems to other aircraft in the experimental area. It was thus decided to try and adapt the droppable pyrotechnic flare system, used successfully to seed tropical cumulus congestus in Florida (Simpson et al., 1970), for use on Alberta hailstorms. This adaptation and testing are described in full by Summers et al. (1971, 1972) but the main features of the seeding system are as follows:

The pyrotechnic flares have a delay fuse of 50 sec, after which the 24 gm AgI mixture burns during the final 30 sec of fall. The distance fallen varies slightly depending on the release altitude, but has been accurately determined by photographic tracking. For the typical drop altitudes used in most of the experiments, the flares fall approximately 10,000 ft in still air with the AgI plume produced during the last 2700 ft of fall. The flares were dropped from a T-33 jet aircraft, equipped and operated by NAE, which was tracked by means of an X-band radar transponder system. The aircraft position was indicated on the same PPI displays as the S-band weather radar data so that the location of the seeding aircraft relative to the target storm was accurately known at all times.

Prior to each experiment a cumulus convection model (Chisholm, 1970b) was run on the latest radiosonde data from Rocky Mountain House or Penhold. From the model output, the -5C level and the updraft profile in the cloud were used, together with the known fall distance of the flares, to determine the appropriate release altitude for each experiment. The flares were dropped into the growing cumulus towers on the flanks (usually the south, but sometimes the west) of well developed storms. In each experiment, several successive developing cloud towers were seeded over a time period ranging from 10 to 90 min of the storm's life. One seeding run was made over each tower and the flares dropped 1000 to 1500 ft apart. Between 10 and 25 flares (240 gm to 600 gm of AgI) were dropped on each run. Seeding rates were therefore of the order of 2000 to 4000 gm of AgI per storm per hour. The number of effective freezing nuclei produced per gm of AgI was 1×10^{13} at -10C, 7×10^{14} at -15C and 4×10^{15} at -20C.

6. SUMMARY OF EXPERIMENTS TO DATE

In July 1970 the seeding system was given a trial in a limited area and five experiments were conducted. In 1971 the experimental area was expanded and the period extended to two months, and as a result experiments were conducted on 11 storms. The details of the number of flares dropped, the observations obtained, etc., in each experiment are summarized in reports edited by Renick (1970, 1971a).

7. RESULTS OF THE EXPERIMENTS TO DATE

7.1 Seeding Logistics

a) The recognition from the aircraft of new developments on the flank of mature storms and subsequent seeding turned out to be quite straightforward and easier than initially anticipated.

b) The required reaction time between the recognition of a new seedable cumulus development and the seeding pass was very short - between 1 and 2 min for active storms.

c) By means of radio communication between the aircrew and the project radar control it was possible to unambiguously identify and seed the target storm in all cases. In 1971 this was made easier by the installation of the X-band transponder system. The transponder gave an accurate fix ($\pm$ 1 mi) of the location of the seeding run relative to the storm radar echo at ranges out to 100 mi.

d) In 1970 a second T-33 aircraft from NAE, equipped to make turbulence measurements, made several penetrations through developing cumulus towers at 18,000 feet (the mean height of the -5C level in severe storms) and found values of the turbulence dissipation rate (ε) between 500 and 1500 $cm^2 sec^{-3}$. Using these values, together with the flare nuclei output at -10C and -15C it was possible to estimate the nuclei concentrations produced in the seeded volume at times up to 10 min after seeding. The results for 2 min and 5 min given in Table 1 show that only 5 min after seeding, a substantial cloud volume will have been seeded with ice nuclei concentrations at least three orders of magnitude above the average natural background.

e) Radar chaff was included in some of the flares and released at the end of the AgI burn. This proved to be useful as a plan position marker; although the X-band transponder enabled the location of the seeding runs to be determined just as accurately. The potential of the chaff as a height marker to test the seeding height targeting accuracy has not yet been fully exploited. This is because a small amount of chaff, with its large axial ratio , could have a large effect on radar polarization measurements, and up to now it has been felt undesirable to drop any into the clouds. The sensitivity of the ALHAS radar is such that the chaff can be detected out to a range of 35 to 40 mi.

f) The system is flexible since the delay fuse in the flares can be adjusted to suit differing target heights, or the flight altitude attainable by the seeding aircraft. The seeding rate can be varied over a substantial range by either changing the amount of AgI in each flare, or the spacing between the flares dropped on a seeding pass, or both.

7.2 Silver Iodide Fallout Patterns

During 1970 precipitation samples were collected by mobile sampling trucks and these were supplemented in 1971 by 233 fixed stations operated by farmer volunteers. These samples were analyzed for silver content using atomic absorption spectrophotometry. In five cases the silver fallout patterns were well documented in space and time (Summers, 1972) and the following conclusions can be drawn from these cases:

a) Although the AgI was initially injected into a relatively small cloud volume its behavior and final disposition varied widely from storm to storm.

b) In all cases some of the AgI was incorporated into the precipitation and was detected at the ground within 12 to 30 min and within 10 to 30 km of the seeding, in a primary fallout zone.

c) In some cases, in addition to primary fallout: some of the AgI had a longer residence time in the seeded storm and did not arrive at the ground in precipitation until 30 to 150 min later, in a secondary fallout zone.

d) In one case, in addition to primary and secondary fallout, some of the AgI was incorporated into the precipitation falling from completely separate storms up to 3 hours later and 80 km away from the initial seeding location, in a displaced fallout zone.

e) A technique has been developed which for the first time makes it possible to detect the location of AgI particles in hailstone sections (Rogers, 1972). Only a few stones have been analyzed so far, but the technique does show considerable potential and should add another valuable input to the evaluation of future experiments.

7.3 Freezing Nuclei Spectra in Precipitation

In addition to the measurement of Ag content, freezing nuclei spectra were determined for half of the samples using the McGill cold stage technique (Vali, 1971). Although a detailed analysis has not been made of these data, the following preliminary results have emerged:

a) The spectra obtained for samples both with Ag and those without showed great variability. No clear-cut difference between the two categories could be found.

b) Large numbers of nuclei active at warm temperatures were always associated with the presence of Ag in the sample. However, the converse was not true, and about an equal number of samples containing Ag had normal type nuclei spectra (the normal being based on many years of data collected from unseeded storms).

7.4 Radar Structure and Silver Iodide Trajectories

Because of the large amount of manual data reduction required, only a few of the seeded storms have been subjected to detailed radar analysis (Renick et al., 1972). In the case of multicell storms the analysis and display technique developed by Renick (1971) was used. This analysis displays a time vs. height history of the radar reflectivity in each cell. These profiles show the initial development of precipitation aloft in a new cell and its subsequent descent to the ground. The rate at which the maximum reflectivity descends is related to the fall speed of the precipitation parcel. Analysis of two seeded multicell storms shows that:

a) The rate of descent of the maximum radar reflectivity in several seeded cells appeared to have a slower descent rate than in unseeded cells, suggesting that the falling precipitation particles were smaller.

b) Precipitation samples containing silver were collected directly under the tracks followed by several seeded cells.

c) Putting a) and b) together with the known time and place of seeding, it was possible to postulate the trajectories followed by the AgI through these cells.

d) When the seeding was done just as the cell was producing its initial radar echo then the Ag was not found in the main precipitation core (usually containing large hail) but at some time later.

e) When the seeding was done several minutes before the initial echo, then Ag was found in the main precipitation core (mostly rain or small hail).

In the case of one seeded supercell storm, it was harder to estimate the trajectories followed by the AgI; however, the following results emerged:

f) In spite of heavy seeding over a period of 90 min no detectable change in the radar structure was apparent.

g) From most of the seeding runs, the AgI appeared to travel up the back side of the storm and miss the main region of precipitation growth.

h) In one case the AgI appeared to travel high through the top of the storm and arrive at the ground well north of the main precipitation core.

i) The above suggests that the AgI was injected into the wrong place and that the seeded cumulus developments were irrelevant to the hail formation process in this storm (see section 4.2).

7.5 The Hailfall Patterns

The patterns of hailfall are notoriously variable from storm to storm and this makes it extremely difficult to use hail size reports and hail damage data to evaluate the physical effects of seeding. However, some trends are emerging:

a) For multicell storms the region of Ag fallout downwind of seeding was generally associated with a reduction of hail size (compared to upwind of the seeding and farther downswath) or a pocket of rain with no hail.

b) No significant damage occurred as a result of hail from any of the seeded cells in a multicell storm; but this was true of some of the unseeded cells also.

c) In the case of the seeded supercell no obvious change in the hail pattern occurred downwind of the seeding and the storm continued on unabated.

d) In several cases after making two or three seeding runs, no further seedable cloud developments appeared and the hailstorm died out soon thereafter; however, this often occurs naturally as storms move east from the foothills.

8. THE 1972 EXPERIMENTS

One of the intriguing findings of the 1971 experiments was that on several occasions, after making two or three seeding runs, no new seedable cloud towers appeared and the storm lost intensity soon thereafter. This suggested that the seeding may be most effective when the storms are caught early in their development, and that perhaps in some way they are prevented from becoming well organized. If this assumption is correct, then it obviously has very important implications regarding operational hail suppression programs. The 1972 experiments were therefore designed to investigate this possibility more fully, as described below.

The Hail Studies project area was split into two parts as shown in Figure 2. An attempt was made to seed all potential hailstorms in the primary target area between 19 June and 18 August. In order to do this a Cessna 320 Skynight was used in addition to the T-33 jet. The Cessna was equipped with racks capable of carrying 104 droppable pyrotechnics. The delay fuse was reduced and the flare AgI payload increased to 50 gm with a burn time of 50 sec. The Cessna was thus able to make seeding runs from approximately 3000 ft lower than the T-33. Otherwise the seeding logistics were essentially unchanged.

During the 1972 program, seeding was carried out in the primary target area on 21 days using a total of 2556 flares. On three other days well documented single-storm experiments were conducted in the northern area. On

several occasions, flares containing radar chaff were dropped into cloud towers on storms near Penhold, and the chaff was successfully tracked for several minutes. A full description of the 1972 experiments is given by Renick (1972).

A detailed physical case-study evaluation is being carried out, but as yet no conclusions can be drawn regarding the effectiveness of the seeding. However, it does appear that a high-performance turbocharged twin-engined aircraft (such as a Cessna 320) is suitable for "on-top" seeding with droppable pyrotechnics. The main drawback is slow speed (compared to a T-33), and occasionally difficulty was encountered in deploying the Cessna from one storm to another rapidly enough. This disadvantage can of course be compensated for by using additional aircraft. In all other aspects the logistics of using a Cessna 320 proved to be as practical as for a T-33.

9. SUMMARY AND CONCLUSIONS

The results to date, while not conclusive, do point in the right direction and are certainly encouraging. The seeding system is logistically simple and can be used to deliver high concentrations of freezing nuclei directly into predetermined locations in Alberta hailstorms. The system has been used only for experimental seeding thus far, but does show potential for being developed into a practical and economical method of large-scale operational hail suppression.

As for the results of seeding, induced physical effects have been detected in the case of multicell storms but not in the case of one seeded supercell storm. In this latter case there is evidence that the seeding material was not delivered into the appropriate part of the storm system. Further experiments on supercell storms should shed more light on this matter. The analyses to date suggest that both time and placement of the seeding material are important when seeding fully developed and active storms. In the case of multicell storms (which are time-dependent), timing appears to be the most critical factor; for supercell storms (which are quasi steady-state), the exact placement appears to be most critical.

Timing may also be important in a broader sense, in view of the finding that the seeding may be most effective when done early in the storms' life - before they have a chance to become well organized. This possibility was investigated more fully by the 1972 experiments.

Perhaps the most important outcome of Project Hailstop so far is that ALHAS now has a highly sophisticated observational and storm monitoring system, and has developed analytical techniques for studying the physical effects of seeding that are second to none. The most promising analytical technique is the one developed by Renick et al. (1972), in which radar data are combined with the known time and place of AgI input and the patterns of Ag fallout, in order to estimate trajectories followed by the seeding material through the storm systems. This is the first time that it has been possible to determine reasonably accurate trajectories through convective

storms and as such represents a significant advance in techniques for evaluating cloud seeding programs. Using the ALHAS approach of physical understanding rather than statistical inference, it is hoped that much of the controversy that has surrounded the statistical evaluation of cloud seeding can be avoided, and that hail suppression programs can eventually be operated on a firmer scientific basis.

10. ACKNOWLEDGEMENTS

Many groups and individuals contributed to the success of the field observational program, the operation of Project Hailstop and the subsequent analyses of the data. Their participation is gratefully acknowledged.

- - - - -

REFERENCES

Chisholm, A. J., 1970a: The radar and airflow structure of Alberta hailstorms. Preprints, Fourteenth Radar Meteor. Conf., Tuscon, Arizona, Amer. Meteor. Soc., 35-42.

_____, 1970b: Estimates of the precipitation growth environment in the updraft core of Alberta hailstorms. Preprints, Conf. on Cloud Physics, Ft. Collins, Colo., Amer. Meteor. Soc., 151-152.

Hitschfeld, W., 1971: Hail research at McGill 1956-1971. Sci. Rept. MW-68, Stormy Weather Group, McGill Univ., Montreal, 67 pp.

Kartsivadze, A. I., 1968: Modification of the hail processes. Proc. Int. Conf. on Cloud Physics, Toronto, 778-788.

Marwitz, J. D., 1972: The structure and motion of severe hailstorms. Part III: Severely sheared storms. J. Appl. Meteor., 11, 189-201.

Petersen, T. A., 1972: Analysis of thirteen years of commercial hail suppression in central Alberta. Agricultural Economics and Rural Sociology Bulletin 13 (Applied Research), Faculty of Agriculture and Forestry, Univ. of Alberta, Edmonton, 51 pp.

Renick, J. H. (Ed.), 1970: Alberta Hail Studies field program 1970. Research Council of Alberta, Hail Studies Report 70-1, Edmonton, 49 pp.

_____, 1971a: Alberta Hail Studies field program 1971. Research Council of Alberta, Hail Studies Report 71-2, 39 pp.

_____, 1971b: Radar reflectivity profiles of individual cells in a persistent multicellular Alberta hailstorm. Preprints, Seventh Severe Local Storms Conf., Kansas City, Mo., Amer. Meteor. Soc., 63-70.

_____, A. J. Chisholm and P. W. Summers, 1972: The seedability of multicell and supercell hailstorms using droppable pyrotechnic flares. Preprints, Third Nat. Conf. on Weather Modification, Rapid City, S. Dak., Amer. Meteor. Soc., 272-278.

_____, 1972: Alberta Hail Studies Field Program 1972. Research Council of Alberta, Hail Studies Report 72-3, Edmonton, 28 pp.

Rogers, L. N., 1972: Use of a simple technique for determining the location of silver iodide particles in hail. J. Appl. Meteor., 11, 745-748.

Simpson, J., W. L. Woodley, H. A. Friedman, T. W. Slusher, R. S. Scheffee and R. L. Steele, 1970: An airborne pyrotechnic cloud seeding system and its use. J. Appl. Meteor., 9, 109-122.

Sulakvelidze, G. K., 1968: On the principles of hail control method applied in the U.S.S.R. Proc. Int. Conf. on Cloud Physics, Toronto, 796-803.

Summers, P. W., G. K. Mather and D. S. Treddenick, 1971: A droppable pyrotechnic flare system for seeding hailstorms. Proc. Int. Conf. on Weather Modification, Canberra, Australia, 349-354.

_____, and J. H. Renick, 1971: Case studies of the physical effects of seeding hailstorms in Alberta. Proc. Int. Conf. on Weather Modification, Canberra, Australia, 213-218.

_____, and L. Wojtiw, 1971: The economic impact of hail damage in Alberta, Canada and its dependence on various hailfall parameters. Preprints, Seventh Severe Local Storms Conf., Kansas City, Mo., Amer. Meteor. Soc., 158-163.

_____, 1972: The silver fallout patterns in precipitation from seeded convective storms. Preprints, Third Nat. Conf. on Weather Modification, Rapid City, S. Dak., Amer. Meteor. Soc., 279-286.

_____, G. K. Mather and D. S. Treddenick, 1972: The development and testing of an airborne droppable pyrotechnic flare system for seeding Alberta hailstorms. J. Appl. Meteor., 11, 695-703.

Vali, G., 1971: Freezing nucleus content of hail and rain in Alberta. J. Appl. Meteor., 10, 73-78.

- - - - -

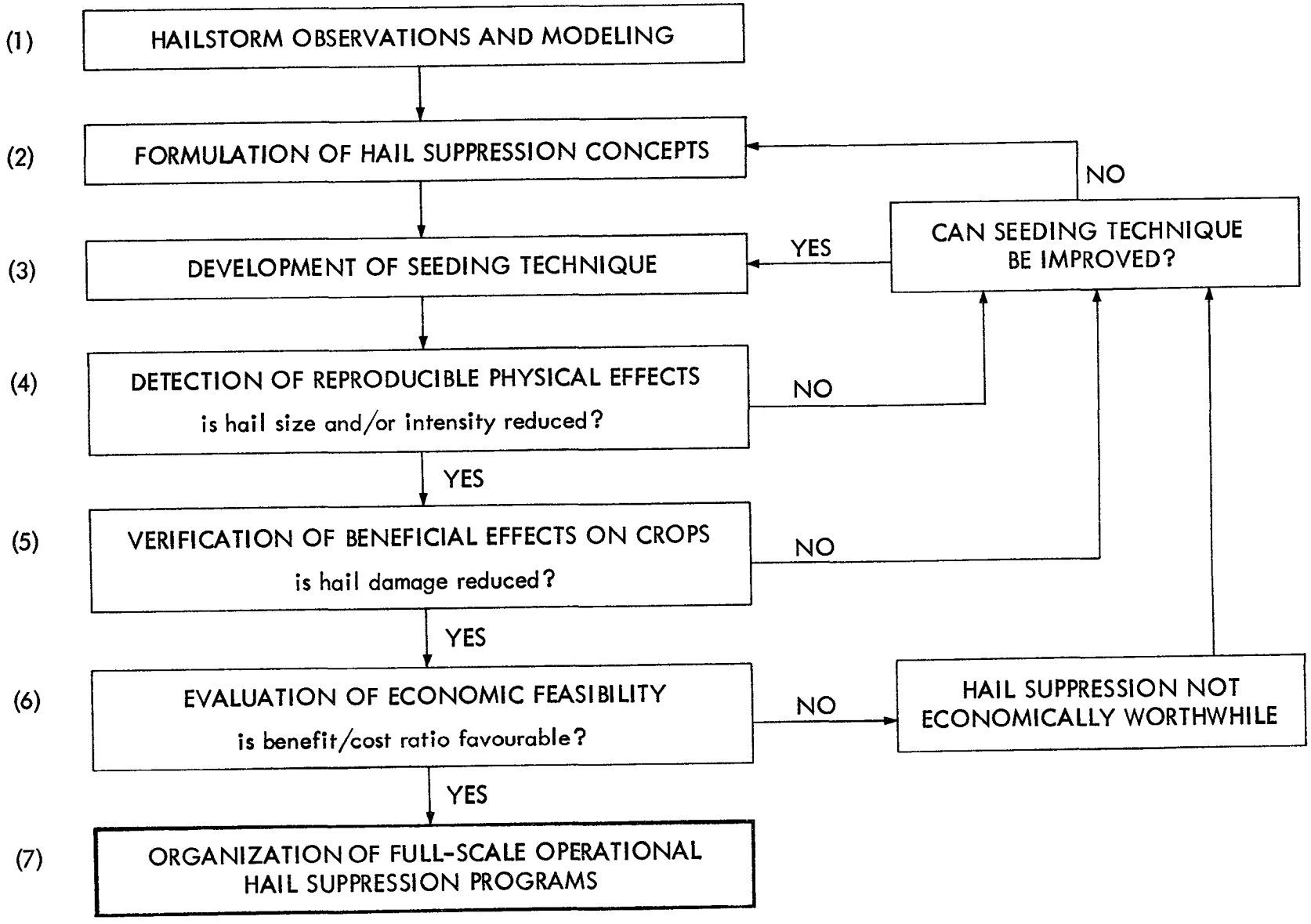


Figure 1.

A plan for developing an operational hail suppression program.

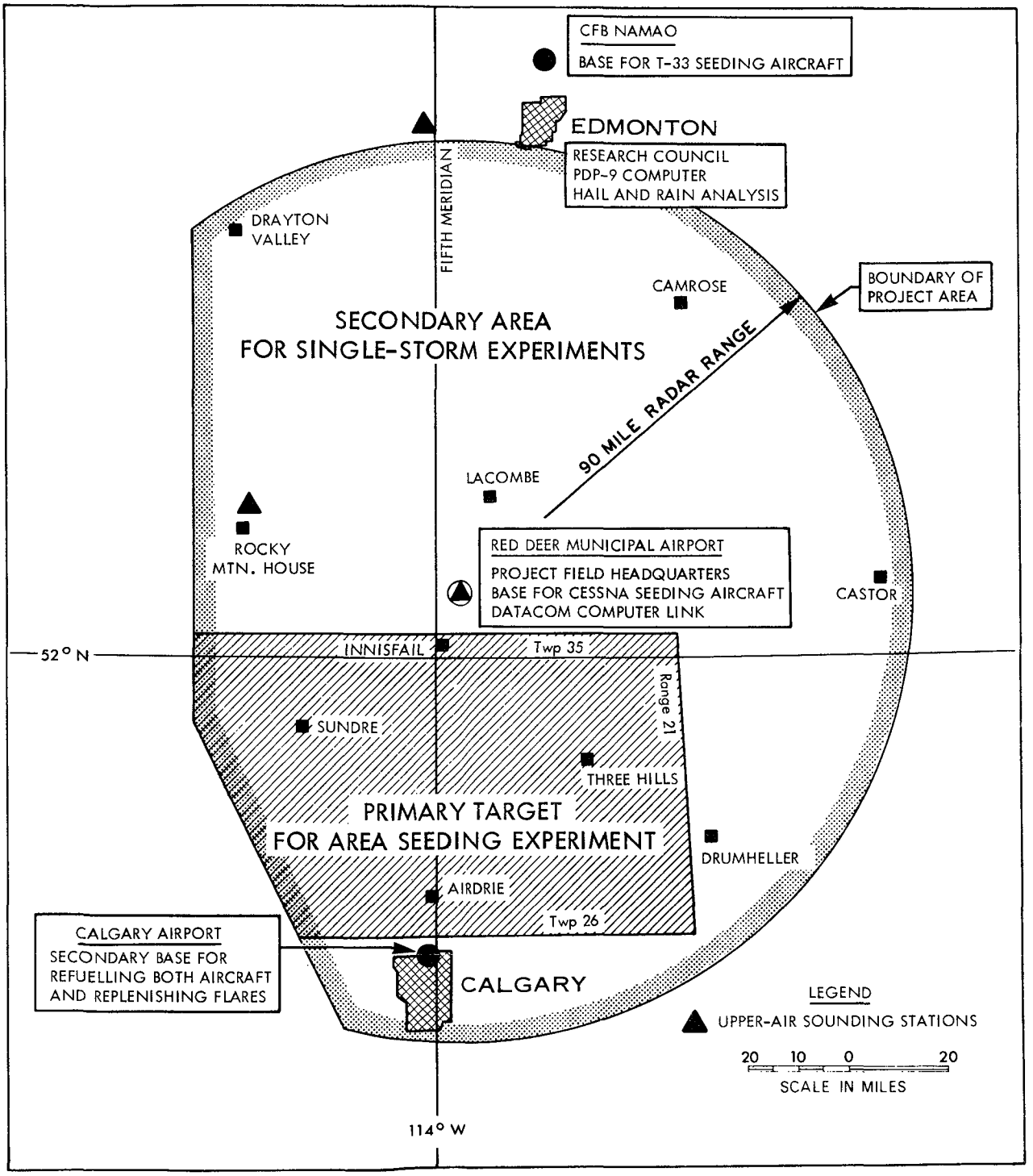


Figure 2.

Facilities and experimental areas for Project Hailstop 1972.

TENTATIVE RESULTS OF FOUR YEARS OF RANDOMIZED SEEDING IN THE JEMEZ MOUNTAINS

C. G. Keyes, Jr., Project Director
F. D. Stover, Project Meteorologist
R. D. Wilkins, Asst. Project Meteorologist
M. Lentner, Consulting Statistician

Prepared for:

Division of Atmospheric Water Resources Management
Bureau of Reclamation
U. S. Department of the Interior
Denver, Colorado

Contract No.14-06-D-6803
January 8- 1973

ABSTRACT

Tentative results of four years of randomized seeding in the Jemez Mountains of northern New Mexico are given in this report. The meteorological partitioning technique used in conjunction with the nonparametric statistical analysis has identified selected meteorological conditions associated with increases and decreases in precipitation while seeding the wintertime storms across the research area. Also, inital estimates of the total precipitation (snowpack) increase producible by multiple meteorological stratifications have been computed for different assumed seeding criteria.

ACKNOWLEDGEMENTS

This research was supported by the Division of Atmospheric Water Resources Management, Bureau of Reclamation, U.S. Department of the Interior under Contracts 14-06-D-6146 and 14-06-6803. Sincere appreciation is due Dr. Archie M. Kahan, Mr. Raymond Girardo, Mr. Clem Todd, Mr. Don Rottner, and Dr. Paul Mielke, Jr., for the valuable suggestions and cooperation in establishing evaluation methods used to obtain these results.

INTRODUCTION

An investigation of orographic snowfall was started in the vicinity of Cuba, New Mexico, in 1968. Randomized seeding began in November of 1968 and has continued each winter season (November through March). At the end of March, 1972, four years of randomized winter orographic seeding was completed in the Jemez and Sierra Nacimiento Mountains in the Rio Grande Basin in northern New Mexico. Figure 1 shows the instrumentation network during the program.

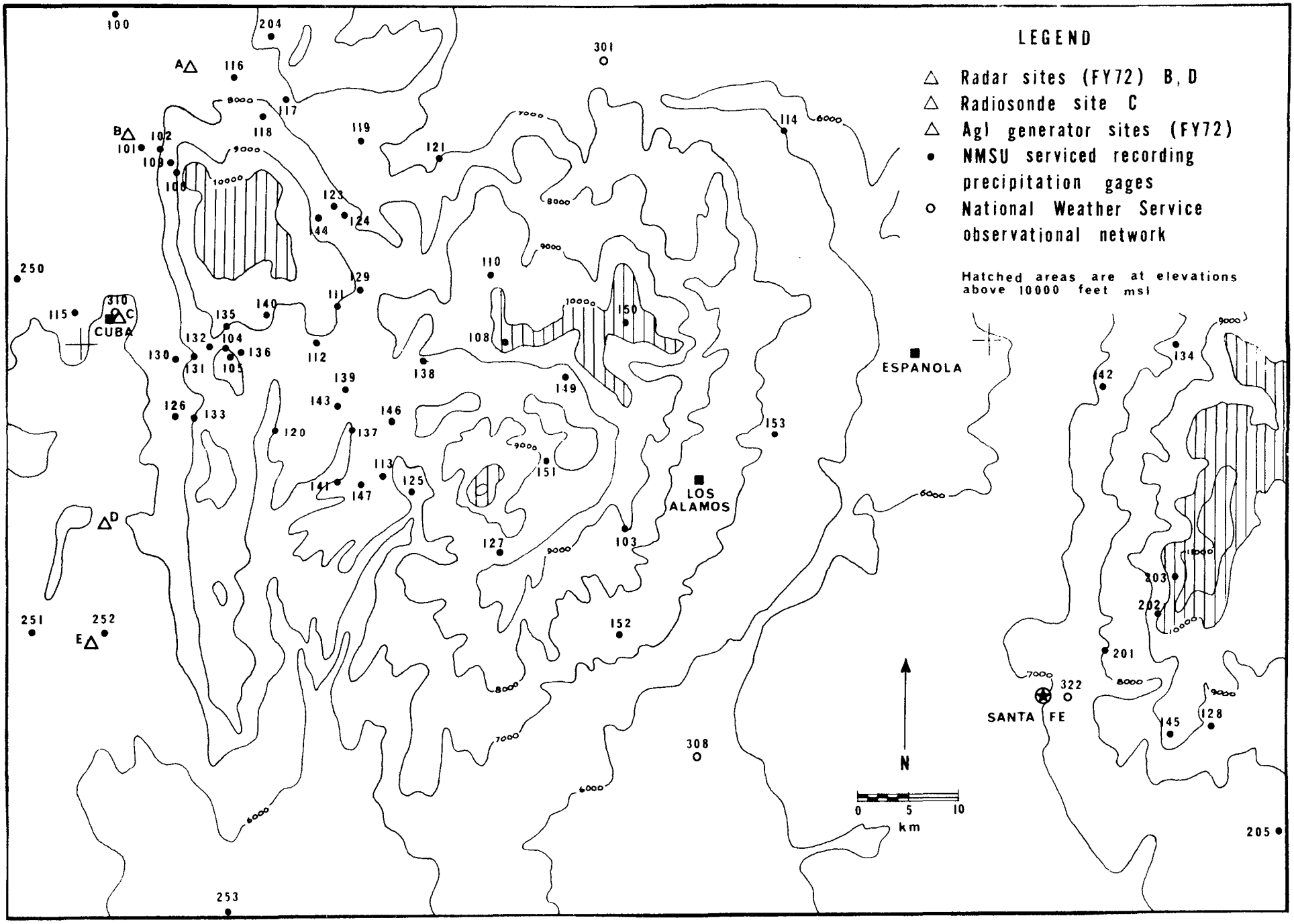


Figure 1. Instrumentation Network

EXPERIMENT DESIGN AND FIELD OPERATION

Detailed reports of the experimental design have been presented by Lunsford et al., (1969, 1970 and 1971). A summary of the important points of the experimental design was reported by Keyes, et. al. (1972). The elements of the experimental design common to the entire four years of seeding were:

1) Randomization was employed to determine the seed or non-seed seedable unit decision.

2) The seedable unit consisted of a 24-hour interval of time.

3) Meteorological measurements were taken in or near the west edge of the immediate target area during most seedable units.

4) Twenty-five recording Belfort precipitation gages were installed in the immediate target area and were serviced by project personnel to provide accurate precipitation data required for the evaluation.

5) The criterion for a seedable unit was at least 0.01 inches of equivalent water at any one of the 25 precipitation stations during the unit had to be forecasted. The project meteorologist(s), who had no knowledge of the seeding decision, made these forecasts.

6) The AgI generators were turned on no sooner than one hour prior to the beginning of a yes-seedable unit and shut down at least three hours prior to the end of the unit unless the following seedable unit was also a randomized yes, in which case seeding was continuous.

7) The immediate target area was considered to be the Sierra Nacimiento and Jemez Mountain ranges between Cuba on the west, Los Alamos on the east, Coyote on the north and Jemez Springs on the south.

Due to some changes in the field operation during the four years, a summary of important elements that may or may not affect the results should be considered.

1) Different lists of randomized yes and no decisions were used in each of the four years of seeding.

2) The seedable unit beginning time was not the same in any continuous year: 0900 MST in FY 1969, 2300 MST in FY 1970, 1100 MST in FY 1971 (corresponded to Upper Colorado River Pilot Project) and 2300 MST in FY 1972.

3) The frequency of the meteorological observations (mainly upper air measurements by radiosondes) was not consistent throughout the four years. The upper air data was obtained at 12-hour intervals throughout the first two years and at least 6-hour intervals the last two years.

4) The locations of some of the precipitation stations changed from year to year based on hydrologic studies that showed high correlations between adjacent stations. These changes decreased the density of gages in some portions of the immediate target area, but filled in the voids which occurred in the early years of the project.

5) The forecasting procedure was different during each winter season. In FY 1969, the seedable unit forecast was made by the project meteorologist after a brief telephone discussion with the National Weather Service (NWS) in Albuquerque. During FY 1970, an objective forecast criteria developed by Stover (1970) was used to predict seedable units occurrence. The FY 1971 forecast was by the Project Meteorologist after he studied the available information at the NWS in Albuquerque. The FY 1972 forecasts were determined by the procedure used in FY 1971, except two forecasters were involved on alternate 10-day shifts.

6) Portable five-gallon AgI generators with NaI as the complexing Agent and a burn rate of approximately 45 grams per hour (or less) were used the first three seasons. The fourth season, new 30-gallon capacity generators with NH_4I as the complexing agent and an approximate burn rate of 100 grams per hour were used from three stationary locations.

7) Three different targeting procedures were used during the four years. The first two years of seeding utilized mobile generators from no more than three locations to affect a small target area near the center of the Sierra Nacimiento Mountain Range. During FY 1971, as reported by Keyes, et al., (1971), generating was performed from Cuba by no more than two of the portable generators. The saturation seeding of FY 1972 (no more than three generators ten miles apart, north and south) was accomplished with the double head burners built in the summer of 1971.

SELECTION OF METEOROLOGICAL VARIABLES ASSOCIATED WITH SEEDING EFFECTS

The ability to specify meteorological conditions associated with a significant positive effect from seeding adds dimension to any evaluation of weather modification research.

An important consideration is in the selection of meteorological variables to be used in the statistical evaluation. The number of possibilities was almost unlimited since radiosondes (upper air measurements) were available in the field (Cuba, New Mexico). The guiding principles used in the selection of the meteorological variables that might be associated with seeding effect are discussed.

Variables Used by Previous Research Projects

Some of the variables that have been associated with a positive seeding effect are: 500 mb temperatures, 700 mb equivalent potential temperature and

700 mb wind direction. The Climax, Colorado research experiment is a good example of the use of these three variables (Mielke, et al., 1971).

Variables Which Represent Measures of Atmospheric Processes

Some of the available variables from radiosondes that represent the processes of stability or moisture content are: (1) 500 mb EPT minus 700 mb EPT, stability through the average depth of cloud layers; (2) mean relative humidity from the surface to 400 mb, moisture available for total seeding effect; and (3) 700 mb temperature-dewpoint spread, moisture at a level which is near the average cloud base.

Variables Related to Cloud Structure Parameters

The temperature structure of clouds could physically represent the temperature ranges which silver iodide is effective. They are: (1) 500 mb (average cloud top) temperature, (2) 700 mb (average cloud base) temperature, (3) estimated cloud top temperature and (4) estimated cloud base temperature.

Variables Arrived at through Professional Intuition

Other variables which could be used are: (1) time of day, (night, morning, afternoon or evening) a variable associated with seeding effect due to night-time inversions or day-time exposure of silver iodide to sunlight; and (2) 700 mb wind direction which should indicate either the silver iodide material being carried toward the effected target area or the material being carried away from the target area.

Variables Selected by the Jemez Project

The variables selected by this project were: time of day code, 700 mb wind direction, 500 mb temperature, 700 mb temperature, 700 mb temperature-dewpoint spread, 700 mb equivalent potential temperature (EPT), 500 mb EPT minus 700 mb EPT, mean relative humidity (RH)-surface to 400 mb, estimated cloud based height, estimated cloud base temperature, and estimated cloud top temperature.

The two estimated cloud temperatures were based on an arbitrary temperature-dewpoint spread definition, which was objectively applied to all radiosondes.

DETERMINATION OF SEEDING EFFECT RANGES FOR EACH VARIABLE

The interfacing of the measured field data with the New Mexico State University statistical evaluation computer program first involved the time definition of the unit for evaluation. This problem arose because of the varying beginning time of the 24-hour seedable unit and the desire to take maximum advantage of the quantity and frequency of field data available.

Definition of 'Analysis Events'

The decision was made to divide each day into 6-hour periods beginning at 2300 MST (The lull of precipitation amounts and events as reported by Stover (1969). This decision can be further justified by noting that a meteorological parameter representing a 6-hour period should be more closely related to physical reality than a single parameter representation of a 24-hour period.

Once the 6-hour periods were defined, called 'analysis events', the next problem was to assign the meteorological and precipitation data to each analysis event.

Assignment of Upper Air Data

The upper air data assignment to each analysis event without consideration of the values of any particular parameter followed the criteria: the closest radiosonde data to the analysis event was chosen or if more than one radiosonde was in or near the 6-hour period, the one closest to the beginning of the analysis event was used to represent that 6-hour period. When the precipitation record was greater near the end of any 6-hour period, a radiosonde closer to this heavy precipitation may have been used as best representing the period.

Assignment of Precipitation Data

The precipitation data for each 6-hour period was obtained by calculating the mean precipitation rate of all active stations over the six hours. This amount would be proportional to the total precipitation received at all of the active stations, since the number of stations in the immediate target area did not vary over the four year period.

Seeding Effect Ranges

Once a variable or combination of variables were selected by one of the four reasons of the last section, the next step was to determine the ranges of each variable associated with a hypothesis of seeding effect (positive, zero, or negative). Normally, a hypothesis is tested on a range of variable (i.e., $-10^{o}C$ to $-20^{o}C$ range of cloud top temperature) for some theoretical reason associated with a positive seeding effect. However, it is also instructive to observe a continuous plot of seed/non-seed ratios over the entire range of each selected variable.

The latter procedure was accomplished by computing a seed/non-seed ratio for overlapping (or running) five (5) degree (or other unit) increments. These values were then plotted on running ratio graphs, Figures 2 through 11. These plots show the range(s) of each variable associated with possibly positive effects (above the 1.0 seed/non-seed ratio line), negative effects (below the 1.0 seed/non-seed ratio line) or zero effect (close to the 1.0 seed/non-seed ratio line).

The curve for each variable was then divided by the vertical lines according to the positive, zero and negative effect ranges to be considered in a statistical hypothesis. The numbers at the top of the vertical lines show the limits of each sector (or range) that was analyzed. The statistical results for each sector (or range) of the variable under consideration appears above and below the arrowed horizontal lines as: (1) top number represents the seed/non-seed ratio for the sector, (2) second number is the sample size (number of 6-hour analysis events) contained in the sector and (3) third and fourth number refer to statistical results described in the next section of this report.

RESULTS OF THE STATISTICAL EVALUATION OF SEEDING

Once the ranges of high and low seed/non-seed ratios have been chosen by the procedure above, a statistical test can be applied to determine the probability that the seeded population does not have the same distribution as the non-seed population. Two different types of nonparametric tests (Wilcoxin and Sum of Ranks Squared) and a parametric t-test were used on the ranges shown on the running ratio graphs. For each sector on the running ratio graphs, the third number represent the nonparametric significance or the probability of saying that the seeded and non-seeded populations are different when in fact they are the same. The fourth number in each sector is the calculated sample size necessary to achieve a parametric significance at the 5% level, assuming a normal distribution of the population.

Examining all of the available running ratio graphs, those ranges of variables which have positive (greater than 1.0) ratios with an adequate significant level should be associated with the meteorological conditions most favorable for achieving a positive effect from seeding. Table 1 gives a listing in order of the best level of significance for the seed/non-seed ratios greater than 1.00. Likewise, Table 2 shows the sectors of meteorological variables associated with possible decreases from seeding.

The overall sample size of the total data set used in Figures 2-11 was 425, which represents the number of cases (analysis events) in which (1) the winds were from the 700 mb wind direction sector of 180-360°, (2) estimated clouds were present with their bases below 7,000 ft. AGL and (3) the average 6-hour precipitation intensity was 0.060 inches per hour or less over the immediate target area. The small sample sizes (100 or less) appear more frequent in the negative results, Table 2, than in the positive results, Table 1.

PHYSICAL INTERPRETATION OF POSITIVE RESULTS

The purpose of this section is to interpret some of the statistical results given in Table 1 and to give additional background where necessary in the physical interpretation of the meteorological variable.

Figure 2.

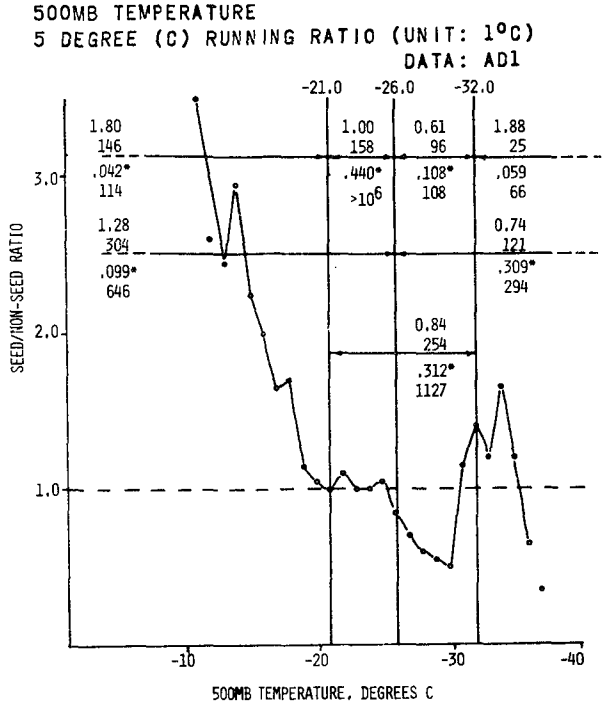


Figure 3.

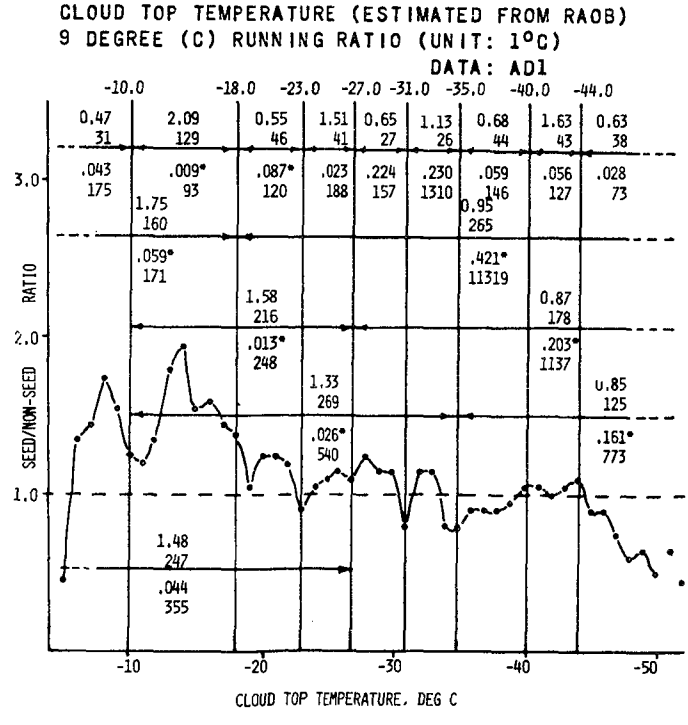


Figure 4.

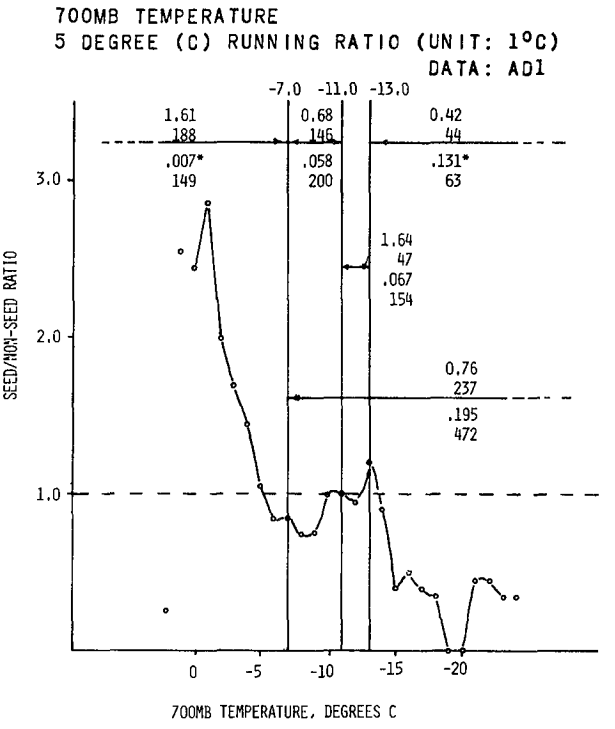


Figure 5.

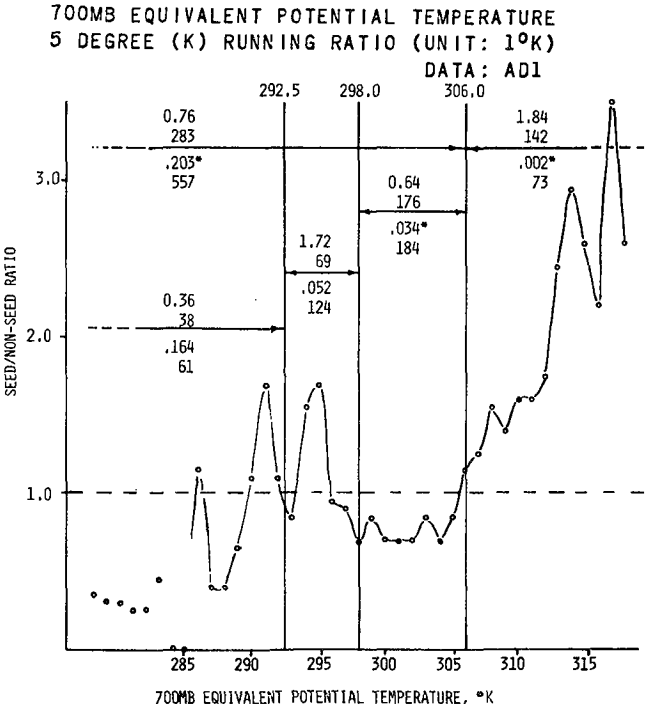


Figure 6.

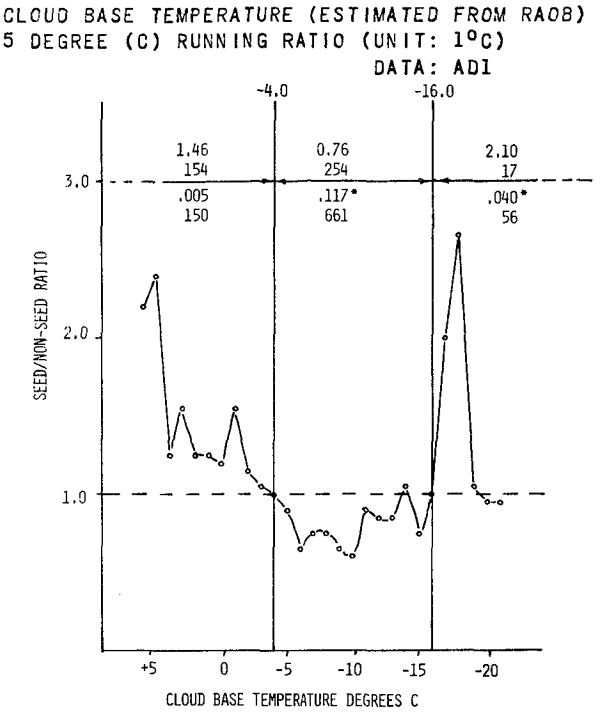


Figure 7.

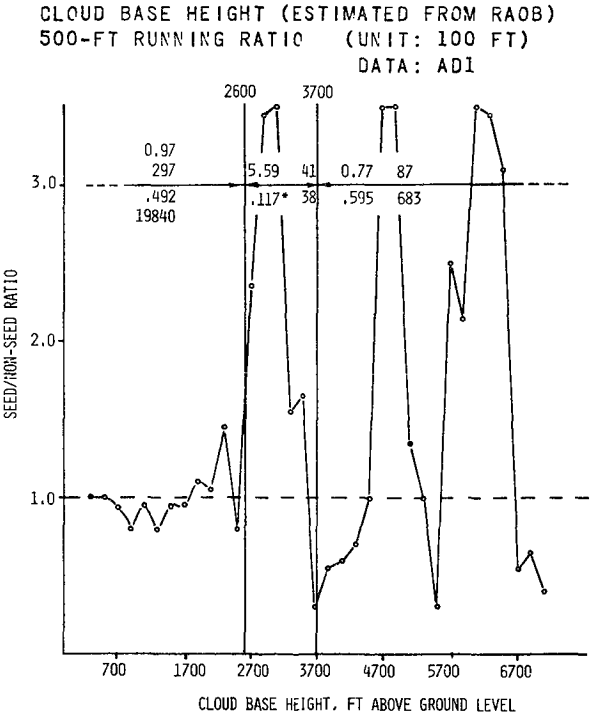


Figure 8.

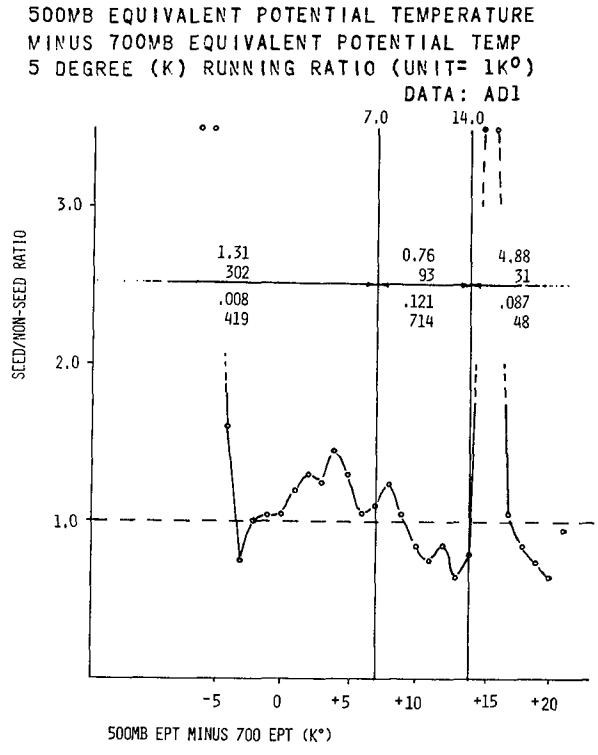


Figure 9.

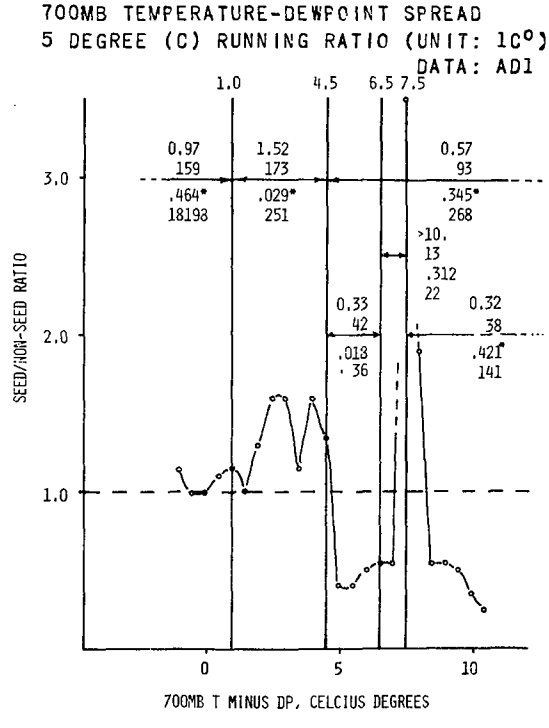


Figure 10.

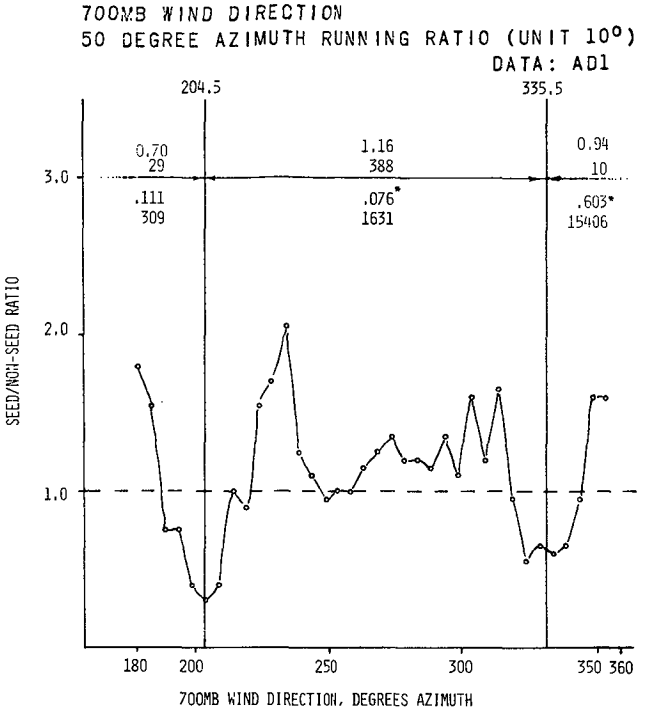


Figure 11.

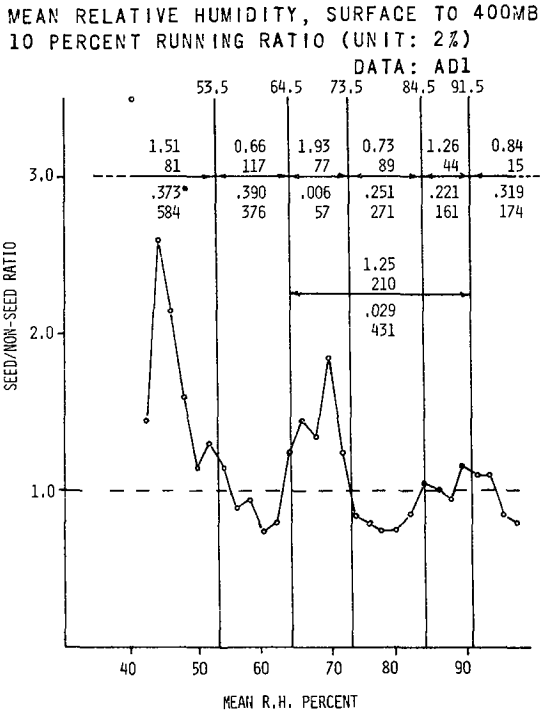


Table 1.

Meteorological Conditions with Significance for Probability of Increasing Precipitation

No.	Meteorological Variable	Range & Units		Seed/Non-Seed Ratio	Sample Size	** NonPar. Signif.	*** Par. Size5%
1	700 mb EPT	306.0	324.0 °K	1.84	142	.002	73
2	Cloud Base Temp	5.0	-3.9 °C	1.46	154	.005	150
3	Mean RH	64.5	73.4 %	1.93	77	.006	57
4	700 mb Temp	3.0	-6.9 °C	1.61	188	.007	149
5	500 EPT - 700 EPT	-15.0	6.9 °K	1.31	302	.008	419
6	Cloud Top Temp	-10.0	-17.9 °C	2.09	129	.009	93
7	Cloud Top Temp	-10.0	-26.9 °C	1.58	216	.013	248
8	Cloud Top Temp	-23.0	-26.9 °C	1.51	41	.023	188
9	Cloud Top Temp	-10.0	-34.9 °C	1.33	269	.026	540
10	Mean RH	64.5	91.4 %	1.25	210	.029	431
11	700 mb T minus DP	1.0	4.4 °C	1.52	173	.029	251
12	Cloud Base Temp	-16.0	-32.0 °C	2.10	17	.040	56
13	500 mb Temp	-10.0	-20.9 °C	1.80	146	.042	114
14	Cloud Top Temp	0	-26.9 °C	1.48	247	.044	355
15	700 mb EPT	292.5	297.9 °K	1.72	69	.052	124
16	Cloud Top Temp	-40.0	-43.9 °C	1.63	43	.056	127
17	Cloud Top Temp	0	-17.9 °C	1.75	160	.059	171
18	500 mb Temp	-32.0	-45.0 °C	1.88	25	.059	66
19	700 mb Temp	-11.0	-12.9 °C	1.64	47	.067	154
20	700 mb Wind	204.5	335.4 °Az	1.16	388	.076	1631
21	500 EPT - 700 EPT	13.9	26.0 °K	4.88	31	.087	48
22	Time of Day	1700	2300 MST	1.36	95	.093	389
23	500 mb Temp	-10.0	-25.9 °C	1.28	304	.099	646

**Nonparametric significance or the probability of saying that the seeded and non-seeded populations are different when in fact they are the same.

***Calculated sample size necessary to achieve a parametric significance at the 5% level, assuming a normal distribution of the population.

EPT - equivalent potential temperature at the designated level.

RH - relative humidity.

Temp - temperature.

T - temperature.

DP - dewpoint temperature.

mb - millibar.

Wind - wind direction.

Table 2.

Meteorological Conditions with Significance for Probability of Decreasing Precipitation

No.	Meteorological Variable	Range & Units	Seed/Non-Seed Ratio	Sample Size	** NonPar. Signif.	*** Par. Size5%
1	700 mb T minus DP	4.5 6.4 °C	0.33	42	.018	36
2	Cloud Top Temp	-44.0 -50.0 °C	0.63	38	.028	73
3	700 mb EPT	298.0 305.9 °K	0.64	176	.034	184
4	Cloud Top Temp	0 -9.9 °C	0.47	31	.043	175
5	700 mb Temp	-7.0 -10.9 °C	0.68	146	.058	200
6	Cloud Top Temp	-35.0 -39.9 °C	0.68	44	.059	146
7	500 mb Temp	-26.0 -31.9 °C	0.61	96	.108	108
8	700 mb wind	180.0 204.4 °Az	0.70	29	.111	309
9	Cloud Base Temp	-4.0 -15.9 °C	0.76	254	.117	661
10	500 EPT - 700 EPT	7.0 13.8 °K	0.76	93	.121	714
11	700 mb Temp	-13.0 -24.9 °C	0.42	44	.131	63
12	Cloud Top Temp	-35.0 -50.0 °C	0.85	125	.161	773
13	700 mb EPT	287.0 292.4 °K	0.36	38	.164	61
14	700 mb Temp	-7.0 -24.9 °C	0.76	237	.195	472

**Nonparametric significance or the probability of saying that the seeded and non-seeded populations are different when in fact they are the same.

***Calculated sample size necessary to achieve a parametric significance at the 5% level, assuming a normal distribution of the population.

EPT - equivalent potential temperature at the designated level.

Temp - temperature.

T - temperature.

DP - dewpoint temperature.

mb - millibar

Wind - wind direction

700 mb Equivalent Potential Temperature

The meteorological condition with the greatest significance for the probability of increasing precipitation was the 700 millibar equivalent potential temperature (700 mb EPT) range, 306.0°K and warmer. The total running ratio plot for the 700 mb EPT appears in Figure 5. The linear correlation between the 700 mb EPT and 700 mb temperature was higher than between any other two variables tested (Keyes, et al., 1972). The running seed/non-seed ration curves (Figures 4 and 5) of these two variables were also very similar (greatest positive effect in the warm end, negative effect in the cold end and a secondary positive effect near the cold end). The similarities would suggest that the two variables are responding to the same physical process, i.e., the peaks in one curve are composed of the same cases as the equivalent peaks in the other curve. In the Jemez experimental area, the 700 mb temperature level occurs at approximately 10,000 ft. MSL which is near the tops of the mountains and probably often in the clouds, near their bases.

Cloud Base Temperature

The meteorological condition with the second best significance associated with the probability of increasing precipitation was the cloud base temperature, values of -3.9°C and warmer (Figure 6). The estimated clouds used in the definition of this variable as well as the cloud base height and cloud top temperature, were not physically observed clouds but rather moisture levels defined by a temperature-dewpoint spread (linear sliding scale of 3.0°C at 700 mb, 4.0°C at 600 mb, 5°C at 500 mb, etc.) on the radiosonde observations. Normally, the observed cloud base agreed reasonably well with the calculated cloud base. However, if precipitation was occurring at the time of the radiosonde observations, the layers beneath the actual cloud base were very moist and thereby defining a cloud base near the ground surface.

Of the total sample used in calculating the seed/non-seed ratios in Figure 6, half of the estimated cloud bases were below 2200 feet AGL and half above this level. Only 96 cases (out of the 425 total sample) were between 2,000 and 4,000 feet AGL, which is the range of the 700 mb level in the experimental area. Since the linear correlation between the estimated cloud base temperature and 700 mb temperature was approximately 0.50, the effects observed in the ranges of cloud base temperature may be due to similar physical processes as observed at the 700 mb level. Also, the signigicant ranges (positive and negative) of both variables had approximately the same seed/non-seed ratio curves, actual sample sizes, and parametric sample sizes to actual sample size ratios.

Mean Relative Humidity - Surface to 400 mb

The meteorological condition with the third best significance for the probability of increasing precipitation was the mean relative humidity (mean RH-Figure 11) from the surface to 400 mb in the range between 64.5% through 73.4%. The expanded range, 64.5% - 91.4%, was also significant, ranking tenth in Table 1. Two explanations supporting the hypothesis that seeding the moist cases (91.5%-100%) would not achieve a positive effect are:

(1) some systems are so moist that they are natural precipitation producers and (2) if heavy precipitation is already falling, artificial seeding material may be washed out of the air before it can penetrate the clouds. The lack of significance in the range drier than 64.4% (Figure 11) suggests that certain minimum requirements of moisture content are required before any positive effect from seeding can result. This variable, mean RH, was relatively independent of most of the other variables tested except for the 700 mb temperature-dewpoint spread, which is also a moisture parameter.

700 mb Temperature

The meteorological condition with the fourth best significance for the probability of increasing precipitation was the 700 millibar temperature in the range of -6.9°C and warmer. This variable is closely related to the 700 millibar equivalent potential temperature which has been discussed.

500 mb EPT minus 700 mb EPT

The meteorological condition with the next best significance associated with a positive seed/non-seed ratio was the 500 mb equivalent potential temperature minus the 700 mb equivalent potential temperature (Figure 8) for all negative values and positive values and positive values less than 6.9°K. Physically, this range of 500 mb EPT minus 700 mb EPT represents conditions of instability and low stability between the two levels. This could suggest that the transport of seeding material through the cloud is the greatest when the mixing in the cloud is optimum. The range of values greater than 13.9°K (condition of extreme stability) ranked 21st in the list of Table 1. Since only 31 cases occurred in this secondary peak and no obvious physical explanation is available at this time, the statistical results for this extreme stable condition should be interpreted with caution.

Cloud Top Temperature

The meteorological conditions ranked sixth through ninth (Table 1) by significance for the probability of increasing precipitation are different ranges of the cloud top temperature (defined above). Three additional considerations were used in defining the cloud top temperature for each radiosonde observation. They were: (1)the defined lowest cloud base had to occur at the 400 mb level or lower, otherwise this was classified as a "no-cloud case"; (2) the cloud top temperature selected, in the case of multiple clouds, was the temperature at the top of the highest cloud; and (3) the temperature at 350 mb was used when a cloud was defined at 350 mb, even though the estimated cloud top was above that level. The most significant positive effect was achieved with clouds whose top temperatures were from -10°C through -17.9°C (Figure 3). Although continued significance and positive effect was achieved by extending the colder end of the range to -26.9°C or -34.9°C, no positive ratio and no significance resulted in the range of temperature colder than -18°C.

700 mb Temperature-dewpoint Spread

The meteorological condition with the eleventh best significance (Table 1) for the probability of increasing precipitation was the 700 mb temperature-dewpoint spread in the range 1.0 through 4.4°C (moderate moist cases in Figure 9). The 0°C to 0.9°C cases (very moist clouds or falling precipitation) had no apparent effect from the seeding which agrees with the extreme moist mean RH conditions.

Other Results

The remaining meteorological conditions with a moderate significance associated with the positive seed/non-seed ratios are described below.

Secondary Positive Ratio Peak - the cold temperature range peak appeared in each of the following variables: cloud base temperature (-16.0 to -32.0°C in Figure 6), 700 mb EPT (292.5 to 297.9°K in Figure 5), cloud top temperature (-40.0 to -43.9°C in Figure 3), 500 mb temperatures (-32 to -45°C in Figure 2) and 700 mb temperature (-11.0 to -12.9°C) in Figure 4.

Main Positive Ratio Peak - the warm temperature range peak of the 500 mb temperature (Figure 2) corresponds to the warm range peak of the 700 mb temperature, both in terms of a high correlation between the two variables and a physical relation based on the mean lapse rate between the two levels. In previous experimental projects, the 500 mb temperature has been assumed to be equivalent to the mean cloud top temperature, however, the linear correlation between these two temperatures for this project was low.

Time-of-day Code - the time period of 1700 through 2300 MST showed a seed/non-seed ratio of 1.36 with a significance level of .093 (moderate significance).

PHYSICAL INTERPRETATION OF NEGATIVE RESULTS

The purpose of this section is to interpret the statistical results summarized in Table 2, which represent the meteorological conditions with the best significance for the probability of decreasing precipitation by seeding with silver iodide. Also, this section will provide additional necessary physical interpretation to supplement the above section on positive effects.

Although the significance level is adequate in some of these negative results (seed/non-seed ratio less than 1.0), the small sample sizes might contain a group of several large random seed or non-seed cases which may not be repeated in an independent experiment, or with additional years of data. When the sample size appears in parenthesis below, the preceding remarks can be applied.

700 mb Temperature-dewpoint Spread

The meteorological conditions with the greatest significance (Table 2) for the probability of decreasing precipitation was the 700 mb temperature-dewpoint spread in the range of 4.5 to 6.4°C (Sample size - 42). A sharp change from the positive effect to the negative effect occurred at the 4.5°C value of this variable, Figure 9. Physically, this inflection point may represent clouds below and clouds above the 700 mb level, respectively. It is not clear why the higher clouds should be associated with possible negative effects.

Cloud Top Temperature

The meteorological condition with the second best significance for the probability of decreasing precipitation was the coldest cloud top temperature range, -44°C through -50°C (Sample size of 38). Also if the range colder than -35°C is observed in Figure 3, there still exists a negative ratio with moderate significance (even though a significant positive minor peak, -40.0 through -43.9°C, was contained within the range). Since the sample size for the cold cloud top temperature range (-35 to -50°C) was 125, the effect of suppression of precipitation by seeding these cold cases is suggestive.

The meteorological condition with the fourth greatest significance for the probability of decreasing precipitation is the warm range of cloud top temperature between 0°C and -9.9°C (Sample size of 31 cases in Figure 3). Although the silver iodide particles become less effective at these warmer temperatures, there is no obvious reason why a decrease of precipitation due to seeding should result instead of the expected results of zero effect.

500 mb Temperature, 700 mb Temperature and 700 mb EPT

The next (seventh, fifth, and third) meteorological conditions with high significance for the probability of decreasing precipitation are three highly correlated variables in the ranges on the running ratio curves (Figures 2, 4 and 8) between the two positive peaks. The ranges of each variable are: (1) 500 mb temperature between -26.0 to -31.9°C, (2) 700 mb temperature between -7.0 to -10.9°C and (3) 700 mb equivalent potential temperature between 298.0 to 305.9°K.

700 mb Wind Direction

The meteorological condition with the eighth best significance for the probability of decreasing precipitation was the 700 mb wind direction in the sector of 180° through 204.4° (Sample size of 29 cases in Figure 10). Although the original design called for no seeding within this wind direction sector, field estimates of the wind direction were often based on surface winds, when the 700 mb wind direction may have been in this sector. However, it would be difficult for very much seeding nuclei to penetrate the target area under this sector, assuming seeding was done. As in several of the observed negative results, it is difficult to understand a decreasing precipitation result rather than a predicted zero result.

Cloud Base Temperature

The meteorological condition with the ninth greatest significance for the probability of decreasing precipitation was the middle range (Figure 6) of cloud base temperature, -4.0 through -15.9°C (Sample size of 254). Since this is a temperature range of effectiveness for the silver iodide material, further investigation is recommended. As stated in the positive results section, a .50 correlation between this variable and the 500 mb and 700 mb temperature group of parameters existed. Also, the running ratio patterns for the variables were similar (main positive effect in warm range, negative effect in middle range and a secondary positive effect in the cold range).

500 mb EPT minus 700 mb EPT

The meteorological condition with the tenth best significance for the probability of decreasing precipitation was 500 mb EPT minus 700 mb EPT in the range 7.0 to 13.8°K (Sample size of 93 in Figure 8). Physically, this range represents moderately stable conditions between the 700 mb (10,000 ft.) and 500 mb (18,000 ft.) upper air levels. Again, the running ratio curve of this variable (Figure 8) was similar to the other standard level running ratio plots (Figures 2, 4, 5 and 9).

Other Results

The remaining meteorological conditions with moderate significance for the probability of decreasing precipitation (Items 11 through 14 in Table 2) are some different ranges of variables which have been discussed above.

SUMMARY OF THE PHYSICAL INTERPRETATION OF RESULTS

The use of the meteorological partitioning technique in conjunction with the nonparametric statistical analysis has identified selected meteorological conditions associated with an increase in precipitation while seeding the wintertime storms that crossed the Jemez Mountain research area. The different conditions with indicated positive results are: (1) 700 millibar equivalent potential temperature warmer than 306°K, (2) cloud base temperature warmer than -4°C, (3) mean relative humidity from the surface to 400 millibars between 65% and 73%, (4) 700 millibar temperature warmer than -7°C, (5) upper air stability above 700 millibars classified unstable or slightly stable, and (6) cloud top temperature range of -10°C to -35°C.

The evaluation has also identified selected meteorological conditions most likely to be associated with a decrease in precipitation during wintertime silver iodide seeding in the Jemez Mountain research area. These conditions with indicated negative results are: (1) cloud top temperatures, which were very cold (colder than -44°C) or very warm (warmer than -10°C); (2) 700 millibar equivalent potential temperature between 298°K and 306°K, which corresponds physically to a 500 millibar temperature between -26°C and -32°C; (3) cloud base temperature between -4°C and -16°C; (4) upper air stability above 700 millibars classified as moderate or strongly stable; and (5) ones difficult to explain (i.e., 700 millibar wind direction from 180° to 204° and 700 millibar temperature dewpoint spread from 4.5 to 6.4°C).

ESTIMATE OF THE TOTAL PRECIPITATION (SNOWPACK) INCREASE PRODUCEABLE BY OPTIMUM SEEDING

The purpose of this section of the report is to: (1) demonstrate a procedure for estimating gross seasonal snowpack increase due to the winter cloud seeding under multiple meteorological stratifications, (2) compute estimates of the total snowpack increase assuming winter seeding under sets of meteorological conditions and (3) determine those conditions which are optimum for winter seeding using AgI ground-based generators. A comparison of the estimated increased snowpack for the seeding windows based on cloud base and cloud top temperatures and 700 millibar equivalent potential seeding windows will also be made.

Selection of the Stratifications

As stated earlier, four years of randomized seeding in the Jemez Mountain area has produced 704 six-hour analysis events. Out of these 704 events, 425 met the following criteria: (1) their 700 mb wind direction was between 180 and 360 degrees azimuth, (2) their cloud bases were below 7000 feet AGL and (3) their mean area 6-hour precipitation rate was less than 0.060 inches per hour. The other 279 events of the 704 were assumed to be unaffected by the artificial seeding. The total precipitation in these 'stratified out' cases was 4266 precipitation units (or 2.56 inches of areal precipitation during the four-year winter period).

The 425 events stratified according to either the cloud temperature window as suggested by personnel of the Division of Atmospheric Water Resources Management or the 700 mb equivalent potential temperature (EPT) window are:

1) 'Cloud Temperature Window', a warm - total of 42 cases which had their cloud base temperature $-5^{o}C$ and warmer cloud top temperature between $-10^{o}C$ and $-20^{o}C$, and 700 mb EPT $306^{o}K$ and warmer.

2) 'Cloud Temperature Window', cold - a total of 20 cases which had the same cloud base and cloud top temperature as above, but their 700 mb EPT was colder than $306^{o}K$.

3) The other four stratifications were made on the remaining 363 analysis events according to their 700 mb EPT. Two of the stratifications are based on the so-called positive effect ranges of this variable (Figure 5); $306^{o}K$ and warmer (warm end) and $292.5^{o}K$ to $297.9^{o}K$ (cold peak). The other two ranges were the so-called negative effect ranges of this variable (Figure 5): $298^{o}K$ to $305.9^{o}K$ and $287^{o}K$ to $292.4^{o}K$.

Precipitation Summary in Each Stratification

The summary of the seed and non-seed precipitation for each of the meteorological stratifications appears in Table 3. The precipitation rates (RS or RNS) in each category (seed cases or non-seed cases) of the six

stratifications was computed by:

$$RS = PS/NS \qquad \text{(Eq.1)}$$

or

$$RNS = PNS/NNS \qquad \text{(Eq.2)}$$

The next step was to estimate the precipitation that would have occurred if no seeding had been performed during the seed cases, PS (NS) and if seeding had actually occurred during the non-seed cases, PNS (S). This was done by applying the non-seed precipitation rate (RNS) to the seed cases and the seed precipitation rate (RS) to the non-seed cases for each stratification. The resulting computations are summarized in Table 4. The equations used for these calculations were:

$$PS(NS) = RNS\ (NS) \qquad \text{(Eq.3)}$$

and

$$PNS(S) = RS\ (NNS) \qquad \text{(Eq.4)}$$

Computation Procedure of Estimating Snowpack Increase

An estimate can be determined for the amount of precipitation increase that might be produced under different assumed seeding criteria by use of the equation:

$$X = 100\%\ (SA - NSA)/NSA; \qquad \text{(Eq.5)}$$

where X is the estimated percentage increase attributable to the assumed seeding, SA is the total estimated precipitation in the assumed seeded stratifications, and NSA is the total precipitation assuming no seeding. The value of the non-seed amount will be constant for all estimations of snowpack increase and is calculated by:

$$NSA = \Sigma PNS + \Sigma PS(NS) + SO; \qquad \text{(Eq.6)}$$

where ΣPNS is the actual non-seed precipitation amount total (non-seed cases in Table 3), ΣPS(NS) is the estimated non-seed precipitation amount for the seed cases (seed cases with non-seed rate in Table 4), and SO is the non-affected precipitation amount (called 'stratified out' cases). The value of NSA equals 14139 + 15993 + 4266 = 34398 for all of the 704 six-hour analysis units.

Estimated Snowpack Increase for the Actual Randomized Seeding

The value of SA in equation 5 for the actual randomized seeding is equal to the total actual seeded precipitation in Table 3 (ΣPS) plus the total actual non-seeded precipitation in Table 3 (ΣPNS) plus the non-affected precipitation (4266 precipitation units), or 15835 + 14139 + 4266 = 34240. Therefore, the estimated percentage increase due to the four years of randomized seeding is:

$$100\%\ (34240 - 34398)/34398 = -0.31\%$$

or approximately no overall effect in the actual snowpack due to the total randomized seeding of the Jemez Project.

Estimated Increase for Assumed Total Seeding

The computations for the estimated percentage increase which might have occurred if all 425 cases had been seeded during the four year period are:

$$X = 100\%(35667 - 34398)/34398 = 3.69\%$$

since $SA = \Sigma PS + \Sigma PNS(S) + SO = 15835 + 15566 + 4266 = 35667$ and $NSA = 34398$.

Table 3.

Summary of Actual Seed and Non-Seed Precipitation Amounts and Rates for Each of the Meteorological Stratifications

Strat. Number	Stratification Description	SEED CASES			NON-SEED CASES		
		NS	PS	RS	NNS	PNS	RNS
1	Cloud Temp.Window-Warm	21	2304	109.71	21	902	42.95
2	Cloud Temp.Window-Cold	9	382	42.44	11	398	36.18
3	700 EPT,287.0-292.4	23	467	20.30	15	903	60.20
4	700 EPT,292.5-297.9	24	1180	49.17	45	1384	30.76
5	700 EPT,298.0-305.9	89	5451	61.25	69	7210	104.49
6	700 EPT,306.0-324.0	49	6051	123.49	49	3342	68.20
	Totals	215	15835		210	14139	
	Inches of Precipitation		9.50			8.48	

NS, NNS: Number of 6-hour cases in each stratification for seeded and non-seeded data, respectively.

PS, PNS: Total precipitation amounts for seed and non-seed categories for each stratification. The "precipitation unit" values are computed for each 6-hour period as the mean areal precipitation rate over the net-workin inches/hour times 10,000. This value can be converted to inches of precipitation for the 6-hour period by multiplying by 6/10,000 or .0006.

RS, RNS: The precipitation rate in "precipitation units per six-hours" for each meteorological stratification in the seed and non-seed categories, respectively.

Table 4.

Summary of the Estimated Precipitation for Each Meteorological Stratification if Seed Cases were not Seeded, and if Non-Seed Cases were Seeded

Strat. Numb.	Stratification Description	SEED CASES W/NON-SEED RATE			NON-SEED CASES W/SEED RATE		
		NS	RNS	PS(NS)	NNS	RS	PNS(S)
1	Cloud Temp.Window-Warm	21	42.95	902	21	109.71	2304
2	Cloud Temp.Window-Cold	9	36.18	326	11	42.44	467
3	700 EPT, 287.0-292.4	23	60.20	1385	15	20.30	305
4	700 EPT, 292.5-297.9	24	30.76	738	45	49.17	2213
5	700 EPT, 298.0-305.9	89	104.49	9300	69	61.25	4226
6	700 EPT, 306.0-324.0	49	68.20	3342	49	123.49	6051
	Totals	215		15993	210		15566
	Inches of Precipitation			9.60			9.34

Where:

PS(NS): The estimated precipitation for the seeded cases if they had not been seeded.

PNS(S): The estimated precipitation for the non-seeded cases if they had been seeded.

NS, RNS, NNS, and RS: Defined in Table 3.

Estimated Increase for Various Combinations of Assumed Seeding

Different estimated effects of assumed seeding can be computed for various combinations of the six stratifications in Tables 3 and 4. Some of the combinations are:

A) Seeding assumed in the Cloud Temperature Window only (stratifications 1 and 2).

B) Seeding in the 700 EPT warm end with the Cloud Temperature Window excluded (stratification 6 only).

C) Seeding all cases in the 700 EPT warm end and the warm Cloud Temperature Window (stratifications 1 and 6).

D) Seeding all cases in the 700 EPT warm end and the Cloud Temperature Window, both warm and cold (stratifications 1, 2 and 6).

	Combination								
	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
(1)	2304	6051	2304	2304	2304	2304	2304	382	1180
	382	902	6051	382	1180	382	398	902	902
	903	398	398	6051	6051	1180	903	903	398
	1384	903	903	903	398	6051	1384	1384	903
(2)	7210	1384	1384	1384	903	903	7210	7210	7210
	3342	7210	7210	7210	7210	7210	3342	3342	3342
	1385	902	326	1385	326	1385	326	902	902
(3)	738	326	1385	738	1385	9300	1385	1385	326
	9300	1385	738	9300	9300	2304	738	738	1385
	3342	738	9300	2304	2304	467	9300	9300	9300
	2304	9300	2304	467	2213	2213	3342	3342	3342
(4)	467	6051	6051	6051	6051	6051	2304	467	2213
(5)	4266	4266	4266	4266	4266	4266	4266	4266	4266
Total Assumed Precipitation Units:	32327	39816	42620	42745	43891	44016	37202	34523	35669
Total Inches of Precipitation:	22.40	23.89	25.57	25.65	26.33	26.41	22.32	20.71	21.40

(1) The first block of data in each stratification comes from the PS column of Table 3.
(2) Data from the PNS column of Table 3.
(3) Data from the PS(NS) of Table 4.
(4) Data from the PNS(S) column of Table 4.
(5) The precipitation assumed not to have been affected by seeding.

Table 5.

Estimates of Total Precipitation Increase by Selected Seeding Combinations

Combination	Percentage Increase	Assumed Number of Seed Cases
(A) Cloud Temp. Window only	100% (37327-34398)/34398=8.52%	62
(B) 700 EPT Warm end only	100% (39816-34398)/34398=15.75%	98
(C) 700 EPT Warm end and the warm Cloud Temp. Window	100% (42620-34398)/34398=23.90%	140
(D) 700 EPT warm end and Cloud Temp. Window	100% (42745-34398)/34398=24.27%	160
(E) Total warm end and 700 EPT cold positive peak	100% (43891-34398)/34398=27.60%	209
(F) 700 EPT warm end, 700 EPT cold positive peak and Cloud Temp. Window	100% (44016-34398)/34398=27.96%	229
(G) Warm end of Cloud Temp. Window only	100% (37202-34398)/34398=8.15%	42
(H) Cold end of Cloud Temp. Window only	100% (34523-34398)/34398=0.36%	20
(I) 700 EPT cold positive peak only	100% (35669-34398)/34398=3.69%	69

Table 6.

Estimates of the Percentage Increase in Snowpack by Selected Seeding Combinations

E) Seeding the total warm end and the 700 EPT cold positive peak, (stratifications 1, 4 and 6).

F) Seeding the 700 EPT warm end, the 700 EPT cold positive peak and the Cloud Temperature Window, both warm and cold (stratifications 1, 2, 4 and 6)

G) Seeding assumed in only the warm end of the Cloud Temperature Window (stratification 1 only).

H) Seeding assumed in only the cold end of the Cloud Temperature Window (stratification 2 only).

I) Seeding the 700 EPT cold positive peak (stratification 4 only).

The computations for each of these nine seeding assumptions are given in Table 5. Based on the computations in Table 5 and using equation 5, the percentage increases assuming various seeding criteria are given in Table 6. The final number in Table 6 represents the number of cases (out of 425) which were assumed by the various seeding criteria to have been seeded. The percentage value is the gross seasonal snowpack increase assuming seeding of all cases in the criterion (or combination) specified, and also assuming that all additional precipitation produced from November through March is accumulated in the snowpack.

Comparison of the Cloud Temperature Windows with the 700 mb EPT Windows

Assumed seeding in the total Cloud Temperature Window (cloud bases -5C and warmer, cloud tops between -10C and -20C) resulted in an estimated 8.52% increase in the total seasonal snowpack or 1.76 inches of precipitation increase. Of this 1.76 inches of precipitation, 1.68 inches would be associated with the 42 cases with the 700 mb EPT of 306K and warmer and only .08 inches of the increase due to seeding would be associated with the 20 cases with the 700 mb EPT colder than 306K.

Although the assumed seeding of only the warm 700 mb equivalent potential temperature window (306K and warmer) might be considered as less efficient (lower seed/non-seed ratio) than the Cloud Temperature Window, the estimated increase is 4.93 inches or 23.90% above the total seasonal precipitation. This higher percentage increase is mainly due to a larger number of cases (140).

If these warm 700 mb EPT cases are combined with the cold peak of the 700 mb EPT cases (700 EPT between 292.5 to 297.9), the assumed seeded 700 mb EPT optimum window would produce an increase of 5.70 inches of precipitation over the four years, or 27.60% net seasonal increase.

Therefore, seeding the 700 mb EPT optimum window is over three times more effective in producing seasonal increases of precipitation than the Cloud Temperature Window. Also, a larger number of cases (209) could be seeded, which would definitely create a larger benefit-cost ratio than only seeding the 62 cases of the Cloud Temperature Window.

SUMMARY

Considering the problems involved in defining cloud top and cloud base temperatures compared to the relative ease and objectivity in which 700 mb parameters can be measured, the implication for an operational project is clear. Namely, a criteria for seeding in future projects in northern New Mexico should use the 700 mb EPT optimum window until such time that a more refined criteria can show significantly better results in overall snowpack increase with at least equivalent ease of measurement and reliability. This assumed 700 mb EPT optimum window can produce a net seasonal increase of precipitation (snowpack) of 27.60%, which amounts to 5.70 inches of precipitation in the four years of assumed seeding or 1.425 inches of precipitation per year (equivalent to approximately 14 inches of snow per year). Assuming an affected area of approximately 500 square miles over the Jemez Mountains, this increase would produce about 40,000 acre-feet of additional water on the ground per year of seeding.

FUTURE PLANS

No further field operations during fiscal year 1973 (last year of present contract) are anticipated. The professional staff of the Jemez Project will continue the detailed evaluation of the four years of winter seeding. This detailed evaluation will include: (1) selection and evaluation of other variables that might be associated with seeding effects, (2) extension of the meteorological partitioning technique to include an evaluation of how two or more variables interact in producing conditions favorable for seeding, (3) effect of seeding on areas other than the main or immediate target area and (4) other statistical methods analysis (i.e., target-control technique in relation with a precipitation regression analysis). At the present time, no major technical problems are anticipated to preclude the completion of the above tasks.

Once the above evaluation of seeding effect is completed, the next logical step would be to organize the results into a set of rules or criteria for seeding to optimize the effect of increasing precipitation. Then climatological surveys could be performed to determine the frequency that these optimum conditions may occur and the economics of precipitation management under these optimum conditions. Due to the limitations of personnel and time, only a satisfactory minimum level of accomplishment should be completed on the above areas.

- - - - -

REFERENCES

Keyes, C. G., Jr., J. V. Lunsford, and F. D. Stover 1971: Preliminary Analysis of Predicting the Seeding Plume Target Stations, November 1970-March 1971, Technical Report No. 72, Engr. Exp. Sta., NMSU, Las Cruces, 65 pp., June.

Keyes, C. G., Jr., J. V. Lunsford, F. D. Stover, R. D. Wilkins and M. Lentner, 1972: Jemez Atmospheric Water Resources Research Project (JAWRRP), Interim Progress Report No. 6 - January 1, 1972 through June 30, 1972, Bureau of Reclamation Contract 14-06-D-6803, Engr. Exp. Sta., NMSU, Las Cruces, 91 pp., August.

Lunsford, J. V., C. G. Keys, Jr., J. Seckler and F. Stover, 1969: Atmospheric Water Resources Research in the State of New Mexico, Final Rept. Bur. of Reclam. Contract 13-06-D-6146, Technical Report No. 51, Engr. Exp. Sta., NMSU, Las Cruces, 144 pp., July.

Lunsford, J. V., C. G. Keyes, Jr., F. Stover and J. Seckler, 1970: Atmospheric Water Resources Research in the State of New Mexico, Interim Rept. - January 1, 1970 through June 30, 1970, Bur. of Reclamation Contract 14-06-D-6803, Engr. Exp. Sta., NMSU, Las Cruces, 83 pp.

Lunsford, J. V., C. G. Keys, Jr., F. Stover and J. Seckler, 1971: Atmospheric Water Resources Research in the State of New Mexico Interim Rept. No. 4 - January 1, 1971 through June 30, 1971, Bur. of Reclam. Contract 14-06-D-6803, Engr. Exp. Sta., NMSU, Las Cruces, 124 pp., July.

Mielke, P. W., Jr., L. O. Grant, and C. F. Chappell, 1971: An independent replication of the Climax Wintertime orographic cloud seeding experiment, Jour. of App. Met., 10, 1198-1212.

Stover, F. D., 1969: Diurnal variations of orographic precipitation in Northern New Mexico, Technical Report No. 52., Engr. Exp. Sta., NMSU, Las Cruces, 44 pp.

Stover, F. C., 1970: An objective forecast algoithm for predicting Precipitation, Technical Report No. 53, Engr. Exp. Sta., NMSU, Las Cruces.

- - - - -

SOME IMPRESSIONS OF WEATHER MODIFICATION DEVELOPMENTS OVERSEAS

Jeremy M. Gosnell
Salisbury, Rhodesia

I have recently had an excellent opportunity of assessing trends of development in weather modification in USA and Australia. During an overseas visit during September-November, I visited ten major centres of activity, attended two conferences on the subject, and made over thirty personal contacts with leading authorities in the field. I was amazed at the number of people actively engaged in weather modification in the USA; there are well over 30 agencies (private firms, universities or government departments) who are carrying out full time operations or research, and the US Department of the Interior has an annual budget exceeding $6,000,000 for research into weather modification. There are half a dozen major firms in the USA who have the capability of mounting a large scale operation anywhere in the world in a matter of weeks. There is a very active Weather Modification Association which holds biennial meetings plus a major annual National or International Congress; the last one was held in Canberra in September 1971 and the next will be held in South Dakota in June 1972. Most scientists I met were very enthusiastic about their field and also extremely helpful.

LONG RANGE VIEW OF WEATHER MODIFICATION

It is 25 years since 1946 when it was first discovered that dry ice and silver iodide could modify cloud behaviour, and since then intensive research has been carried out in the USA, Australia and elsewhere on many aspects of weather modification, notably rain making. During the early years there were numerous conflicting reports of results by serious experimenters and many charlatans operated in the commercial field. Thus that it has only been during the last five years or so that scientists have accepted the fact that weather modification can and does work provided that it is carried out under the correct conditions. Numerous well authenticated reports have been made of successful rain making, hail suppression and fog clearing operations, while investigations into lightning prevention and hurricane wind force reduction are currently being carried out.

Several authorities stressed that a single drought relief campaign in a new area may or may not be successful due to lack of knowledge of the detailed interaction of the meteorological conditions present. Greater success is usually achieved by a sustained effort over a number of years since improvements can be made in the light of increased knowledge of local meteorological conditions. Such programmes have frequently lasted many years, e.g. a cloud seeding program initiated in 1954 in the Kings River catchment in California has increased runoff by over 80,000 acre ft. annually. It is still continuing and has recently been extended to include summer convective as well as winter orographic clouds. Where the operations have been successful, the water produced is usually very substantially cheaper than that obtained from any other source. These considerations have led to an outlook which may best be described as the use of Atmospheric Water Resources Management as an additional tool which the agriculturist can use to maximize profits, together with the other tools at his disposal, i.e. irrigation, fertilization, etc.

RESEARCH VS. OPERATIONS

Weather modification experiments are characterized by careful attention to statistical evaluation of a randomized Seed/No Seed choice while detailed measurements of cloud conditions and rainfall are taken in both instances. Much of the work has been done on isolated clouds because of the greater ease and accuracy of measuring responses. However more recent research has been concerned with larger target areas including mesoscale cloud formations, and catchment areas where the prime measure is runoff rather than rainfall.

Many operators now feel sufficiently confident about the validity of their research successes and have moved into area operations in which essentially all clouds are seeded to maximize response and to achieve commercially worthwhile yields of rain. Unfortunately, this results in a very large loss of information on the success or otherwise of the operation, and considerable reliance must be placed on subjective evaluation by the meteorologist concerned, together with rainfall and runoff comparisons from neighbouring unseeded areas. There can be no doubt, however, that a tremendous amount has been learnt from these operational techniques, and by far the majority of useful artificial precipitation so far induced has been the result of this type of operation.

TYPES OF CLOUDS AND MATERIALS USED

There is considerable interest in the use of salt and other hygroscopic materials for warm cloud seeding (see Sugar News No. 11, p. 1) especially in the hotter areas where warm clouds form a large proportion of the total. However, this method is still experimental and no major operations have yet successfully utilized the technique.

Supercooled clouds may be seeded with a number of compounds including metaldehyde, dry ice, lead iodide and silver iodide, and many other compounds are being tested for activity. Dry ice has been successfully used by a number of operators and we are planning to test it out in Rhodesia. However, the great majority of work has been done with silver iodide, except in Russia, where lead iodide is commonly used.

Most successful operators use pyrotechnic methods of dispersing the silver iodide. These fall into two main categories:

(a) Very type cartridges, which are either fired manually from a Very pistol mounted in the side of the aircraft, or fixed below the wing and fired electrically from the cockpit. Manually operated Very pistols are being used in the Kyle operation.

(b) Fusees, which are long (12-20 in.) continuous burning flares mounted beneath the wing and ignited electrically from the cockpit.

These techniques are used either above the cloud or for penetrating the cloud at altitudes of 18-21,000 ft.

Some operators use another method in which a solution of silver iodide in acetone is burnt from a specially constructed burner mounted on the aircraft which is flown either below the cloud or through it at about 14,000 ft. This method is being used by the Meteorological Department in their experiments which have been carried out for the last three years, and are continuing this year.

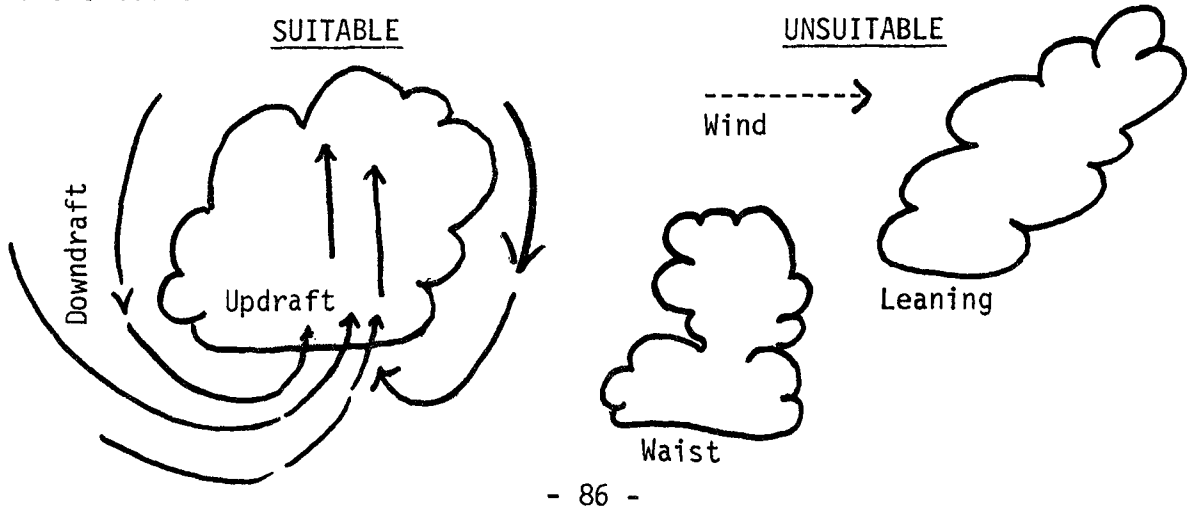
RESULTS

Appreciable and statistically significant increases in rainfall have been reported by scientists in many areas, e.g. New South Wales, Victoria, California, Arizona, Utah, Colorado, Florida, Israel, Philippines, Ryukyu and Russia. A number of unsuccessful operations and instances of decrease in rainfall have also been recorded. However, these negative or zero results have all helped to yield information on the types of conditions required for success.

CLOUD CONDITIONS REQUIRED FOR SUCCESSFUL OPERATION

The prime requirement is that the top of the cloud reaches a minimum altitude of 18-21,000 ft., which corresponds with a temperature of -4 to -10°C. Cloud tops of 21,000-25,000 ft (-10 to -18°C) are ideal, while those higher than 30,000 ft (-26°) are generally not suitable, although these large clouds often have suitable turrets around them which may be seeded. The depth of the cloud should be at least 6000 ft, and it should be greater that the height of cloud base above ground. Unless these conditions are met, the drops will not have developed to sufficient size before falling out of the bottom of the cloud and they may evaporate before reaching the ground. Suitable clouds have a wide base of at least 1-1½ miles and should not have a pronounced "lean" (caused by wind shear) or "waist" which may result in the top of the cloud separating. Seedable clouds are those with a hard cauliflower-like appearance which are still growing in height. They also have a high liquid water content.

It is important to place the silver iodide in the updraft of the growing turret, and the correct quantities must be used. Precipitation may easily be decreased if a decaying cloud or the downdrafts of a cloud are seeded, or if too much silver iodide is used in a cloud system of inadequate size. This is because too vigorous updraft activity in the cloud may draw dry air in from outside the cloud and result in the top of the cloud being blown off into a cirrus shield.



THE DAILY OPERATIONAL PROCEDURE IN THE KYLE PROJECT

Radiosonde balloons are sent up each morning at 6 a.m.; these yield data on temperature and humidity at increasing altitudes which is plotted graphically or processed by computer to give information on whether conditions are likely to be suitable on that day. A decision is then made by about 10-11 a.m. each day whether or not conditions will permit flying. If in doubt, the aircraft will fly to ensure that all possible opportunities are taken. The aircraft will normally take off about 12 noon and fly for about 4-5 hours during the afternoon which is the most active period of the day for development of cumulus clouds. A cloud seeding officer flies with the pilot on each occasion as this is essentially a two-man team operation. The aircraft and team will be on a 7 day per week standby from the beginning of December (when the operation actually commenced) until the middle or end of March. At present, the standby aircraft, a Beechcraft Baron, is in use, but it is expected that the turbocharged Cessna 210 will be available shortly.

OTHER OPERATIONS IN SOUTHERN AFRICA

No significant work on cloud seeding has been carried out in South Africa up to now, but this summer two major operations are in progress, both employing professional American operators.

The Laeveldse Tabakkooperasie Bpk. at Nelspruit have given a contract to the Sierra Research Corporation of Boulder, Colorado to carry out hail prevention and rain making operations over some 4000 sq. miles of the Eastern Transvaal.

The South African Weather Bureau has also authorized a large scale experimental project to be carried out under the auspices of the insurance group Sentraoes, based at Ficksburg. The contract for this project has been given to Atmospherics Inc. of Fresno, California, and will cover a large area in the Vaal catchment around Bethlehem.

- - - -

SEEDING SINGLE CUMULUS CLOUDS IN RHODESIA WITH SILVER IODIDE:1968-69

D. L. McNaughton

Department of Meteorological Services
Causeway, Salisbury, Rhodesia

Isolated cumulus clouds with supercooled tops were either seeded from an aircraft or left alone, according to randomised instructions. The amounts of rain which then fell from both categories of cloud were measured from the aircraft using a rain collector and an impactor. The seeded clouds yielded much more rain than the untreated ones, even though there was no significant difference in cloud depth at the time of selection. The duration of rain from the seeded clouds was also significantly longer than that from the other clouds. Tentative conclusions regarding the temperatures and updraughts in the clouds, the time lag between seeding and rain, and the degrees of isolation of the various clouds are also discussed.

Rhodesia is a tropical country with its rainy season freezing-level at about 5000 metres above mean sea level, but is on a high plateau several hundred kilometres from the sea. All these factors affect the physical processes in its clouds, and it is therefore impossible to be sure how cloud seeding techniques practised elsewhere would work in Rhodesia. These experiments were intended to answer basic questions, such as the cloud size and cloud-top temperature necessary for silver iodide treatment to increase the rain, and the time interval between seeding and the production of rain. This kind of work is an essential preliminary to any cloud-seeding exercise designed to detect changes in the rainfall of an area.

The procedure adopted was similar to that used by CSIRO, Sydney, in their experiments between 1962 and 1965 (Bethwaite et al., 1966).

EQUIPMENT

Twin burners were mounted below the aircraft fuselage. Each one was fed at a rate of 9 litres per hour with silver iodide solution from a stainless steel tank fitted with controls for the flow and ignition of the solution. Peep-holes or mirrors enabled the burner flames to be checked during flight. The solution consisted of 4 parts of silver iodide and 1 part of sodium iodide dissolved in about 50 parts of acetone, all by weight.

A rain-drop impactor was made to the same basic design as the one used by the CSIRO in Australia to measure the rain in their single cell experiments (Bethwaite et al., 1966), and was mounted on the nose of the aircraft (Figure 1). Raindrops which enter the aperture make permanent impressions on a strip of aluminium tape which winds slowly over the drum. The tape was exposed to rain for 0.6 seconds every 6.25 seconds by the opening of the shutter. In heavy rain it was found that this led to too much overlapping of drop imprints, and so at the beginning of February the exposure time was reduced to 0.35 out of 6.25 seconds.

A time marker also made imprints on the tape, which were easily distinguishable from those of the raindrops, and during rain-measuring runs it was set to make marks at regular intervals of 6.25 seconds. At the beginning and end of every run it was operated manually, marking the appropriate point on the tape with a pair of imprints one second apart. The largest drop sizes encountered were sildom more than 3.5 mm in diameter, and on this basis, using the calibration in Australia of their own impactor, it was assumed in our calculations of rainfall that the ratio of imprint diameter to drop diameter was 1.3 to 1.

A rain collector was mounted 250 mm above the skin of the fuselage just aft of the pilots' compartment. The basic design was taken from the scoop used by Prof. Ostlund to collect water samples from an aircraft in hurricane "Betsy" off Florida in 1965 (Ostlund, 1968), and is shown in Figure 2. A standard 5-inch (127 mm) raingauge rim mounted on a smoothly moulded funnel formed the collecting aperture. This led via a 25 mm bore tap into a separating chamber in the aircraft, from which the air escaped at the top, leaving the water to be collected and measured from the bottom. It was necessary to close the tap before measuring the volume of rain collected, because there were times when it seemed that the air-flow was causing some water to remain trapped in the separating chamber. Before the tap was fitted the air-flow would sometimes even force water drops out of the air exit at the top of this chamber.

A clinometer compass was carried in the aircraft, and used to estimate the top heights of selected clouds.

A camera was used to assist the compass with its height readings, by providing photographic records of the appearance and growth of the clouds.

Radiosondes were sent up at dawn from Salisbury every day. These gave the temperature, stability, and water content of all levels of the atmosphere where cloud development is possible. This information enabled suitable experimental days to be selected, and top temperatures of clouds to be estimated. Daily radiosonde information was available also from Bulawayo and Kabwe, and was useful for clouds selected a considerable distance from Salisbury.

Figure 1.

Raindrop impactor

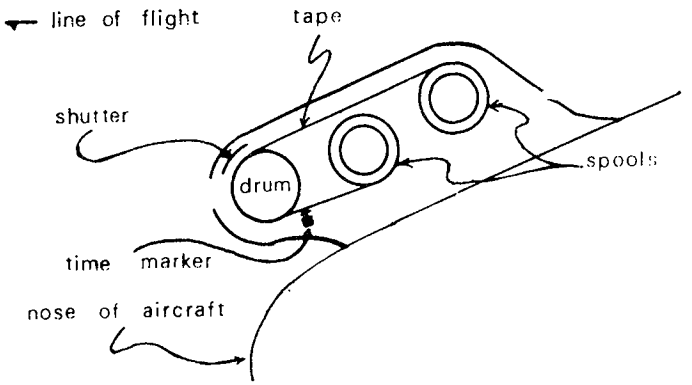
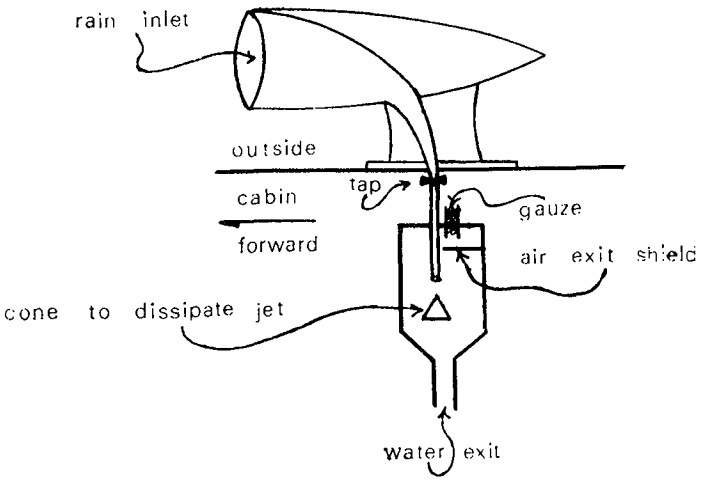


Figure 2.

Rain collector



CLOUD SELECTION PROCEDURE

A cloud was regarded as suitable for experiment if it met the following specifications:

(a) It had to be a solid-looking cumuliform cloud which was still growing and not yet glaciated, and likely therefore to provide updraughts strong enough to carry the silver iodide to the higher portions of the cloud.

(b) It had to be -5°C or colder at its top, because experiments elsewhere (Smith and Heffernan, 1968), have established that silver iodide smoke does not provide the freezing nuclei necessary for successful seeding unless at a temperature colder than -4°C. It was decided that the cloud had to reach a level where the free air temperature was -6°C or colder, because if the cloud was to continue growing its temperature would need to be warmer than the corresponding free air temperature.

(c) The cloud had to be separated from others of comparable size, and at least 8 km from any cloud giving rain.

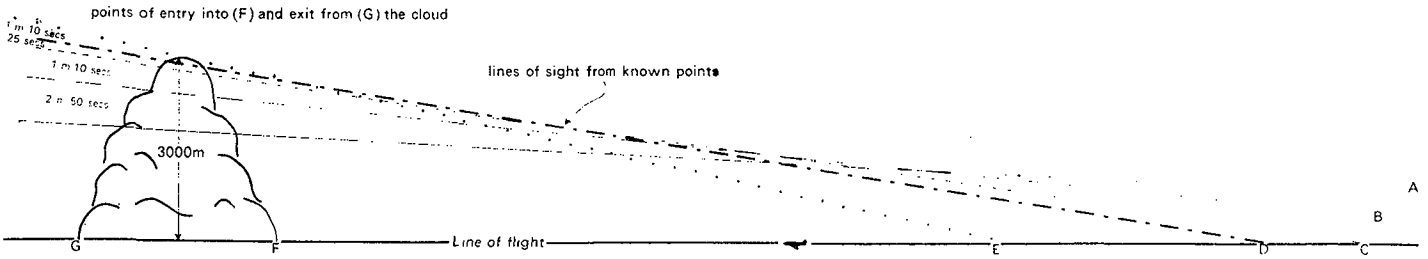
During November and December the clouds were chosen from 6000 m, (all heights are above mean sea level), which was usually the -6°C level and at or not far below the cloud top. The aircraft would then descend to cloud base for the seeding and rain-measuring operations. However, this nearly always resulted in rain staring before seeding could commence. It was decided, in the remaining months, to select the cloud at the lowest level which gave a

clear view of the horizon, usually about 4,000 m, and to seed at the same level. In the earlier case clouds were not selected unless they had flat substantial bases; in the later months the seeding level of 4,000 m was nearly always high enough to be well above the ragged sections of clouds with poor bases, and after a few successful trials (described in Appendix D but not included in the statistical sequence) it was decided to relax the insistence on firm bases for selected clouds.

In every case an estimate of the cloud top was made by eye, just before selection. When these estimates were made from the 4000 m level, in January and after, this estimate was checked by using the clinometer compass to read the angle of elevation of the cloud top from known points on a level flight straight towards the cloud. The time and aircraft speed were noted for every compass reading and also for entry into and exit from the cloud. A drawing was then made later of the lines of sight, and a probable approximate cloud outline at the time of entry was inserted into the drawing, bearing in mind that the sighted tangent surface was lower than the actual cloud top. Attempts were made to check and allow for cloud growth between the compass readings by taking photographs to coincide with each compass reading, and taking another photograph on the second seeding run (orthogonal to the first) to see whether and even allow in the drawing for the fact that the cloud was leaning. An example of a crawing made using compass readings is shown in Figure 3.

Figure 3.

Height estimate of cloud on 1 February 1969



SEEDING

A truncated random sequence was used to determine whether the selected cloud was to be seeded or left alone, the appropriate instruction being obtained by opening an envelope after the selection had been made. For both categories of cloud treatment four seeding runs were made, although the aircraft would descend immediately to cloud base for rain measurement if the collector showed the water content at the level in the loud to be high. Notes were made on the strengths of the vertical currents encountered during the runs, in both seeded and non-seeded clouds, using the instantaneous vertical speed indicator in the aircraft.

RAIN MEASUREMENT

As far as was possible the measuring runs were made through the heaviest part of the rain in two fixed orthogonal directions alternately. Successive runs were about five minutes apart, and for each one the duration of the flight through rain and the true airspeed gave the dimension of the shower at that instant in that particular direction. Rain measuring runs continued until the cloud stopped raining, whenever possible. During every run through the shower the impactor tape was exposed to rain, and the volume of water scooped up by the collector was measured and recorded.

DESCRIPTION OF THE EXPERIMENTS ON 15thJANUARY 1969

This was an interesting day, because it provided the opportunity to observe both a seeded and a non-seeded cloud. The morning radiosonde at Salisbury showed moist air near the surface and very dry air aloft. The Bulawayo sounding was considerably moister than Salisbury at nearly all levels of the atmosphere. This information suggested that suitable isolated clouds would develop late in the afternoon to the west or south-west of Salisbury. The necessary $-6^{o}C$ level was at 5,800 m.

A cloud whose top was estimated to be about 6,400 m was selected near Lake McIlwaine, and the next envelope in the sequence was opened but the instruction was "Leave it alone". Compass readings were taken of the cloud top from about 5200 m above sea level, which when worked out later gave the height of the top at 6500 m, at a temperature of $-9.5^{o}C$. Very strong updraughts were felt as soon as the aircraft entered the cloud, 300 m per minute being recorded on the vertical speed indicator. However, within 12 to 15 minutes the cloud had collapsed, giving no rain.

About 20 minutes later another cloud was selected twenty miles north of Hartley with a top estimated to be about 5800 m ($-6^{o}C$), this being confirmed later by the compass readings. This time the instruction in the envelope was "Seed". Moderate updraughts were felt during all four seeding runs, and a strong one (250 m per minute) was felt on the second run. A few downdraughts were also felt on the first and fourth runs. The first seeding run was made at 4500 m, and the others were at or just above cloud base, at 3400 m. No water was collected from the cloud at all, during seeding. Two more compass readings were taken just before the fourth seeding run, about 11 or 12 minutes after the first run, when the silver iodide could be expected to have stimulated the cloud at its top. These suggested a height of 7,600 m and a temperature of about $-16^{o}C$. However, these readings were taken from cloud base level, compared with 5200 m for the earlier set, and were probably less accurate, therefore.

Rain began about 18 minutes after the first seeding run, and reached a maximum three or four minutes later. It then decreased to almost nil. However, 23 minutes after the very last seeding run brought another sharp increase in rain, with a maximum nine minutes after that. The total rain duration was 38 minutes and the total rainfall was 80×10^{3} m^{3} (using the collector). The nearest rain from any other cloud was 65 km to the north-west.

ESTIMATE OF TOTAL RAINFALL

Graphs were plotted of the variation in time of the north-south and of the east-west dimensions of the shower, or of whichever orthogonal directions were used to make the rain measurements.

The ranking of the clouds was then based on the integration of the quantity Vb over the lifetime of the shower, where V is the volume of water collected or recorded during the run, and b is the width of the shower perpendicular to the run at the time of collection of the volume V. In the circumstances it is fair to assume that this gave the best estimate of the total rain that fell. The volume of air sampled by the impactor is too small to justify evaluation of the rain profile, as a means to a more accurate answer, and the same would probably apply to a more complex design of collector. It was decided that the most practical approach was to use the formula applicable to a rain shower whose intensity profile is symmetrically parabolic, and in Appendix A it is shown that the total rain content of such a shower, at any given instant, is proportional to this product Vb. Even if the shower profiles were markedly non-parabolic, it is almost certain that the ranking of the clouds according to comparisons of their quantities Vb was the correct one.

Some single cloud experiments (e.g. Smith, 1950) have made use of radar measurements to assess the rain content of the showers. Since the intensity of the radar echo is proportional to the sixth power of the drop diameter, and the water content only to the third power, it is doubtful whether this method of ranking the clouds was any better than ours;both methods can only give estimates of total rainfall.

Thus another graph was drawn for each cloud, of the variation in time of the quantity Vb, and the area under the graph gave the estimate of total rainfall. b was obtained by interpolation from the graphs of linear dimensions against time. An example of the graphs drawn is shown in Figure 4. In order to convert the rain content Vb to rate of rain flow it is necessary to assume that a single representative value of the drop-fall speed could be used to apply to all cases, for the purposes of comparison. The rate of rain flow is then given by the product of the rain content and the drop-fall speed.

A discussion of the comparative values of the volume of water scooped up by the collector and that recorded by the impactor (corrected for exposure time) can be found in Appendix E, and the results suggest that the collector's volume is probably nearer the true one in heavy rain, and the impactor is better in light rain. The conclusions have been based therefore on collector readings, although both sets of results are submitted.

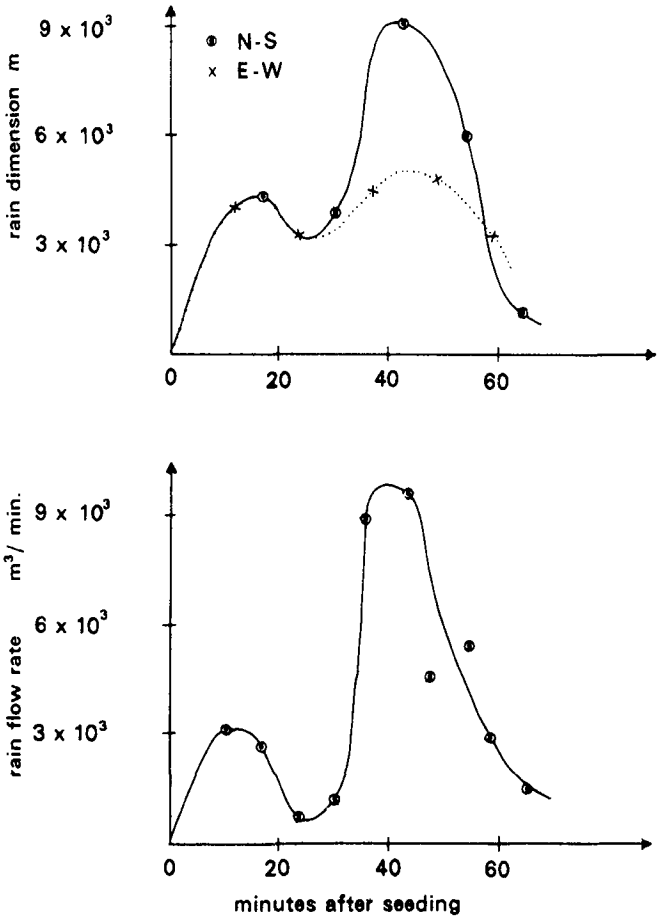
RESULTS OF EXPERIMENTS

Table 1 shows in chronological order the list of clouds belonging to the random sequence. (On 22nd November 1968 the rain dimensions were measured approximately, and the only record of rain intensity is the co-pilot's impression of the rain on the aircraft windscreen. Comparing this with another experiment recorded by the same co-pilot suggests that the 22nd November might

rank about third or fourth in the sequence, but it has not been included in the statistical treatment of rainfall amount.) The cloud-top temperatures and cloud depths are estimated values at the time of selection using the clinometer compass readings.

Figure 4.

Sample rain measurement on 26 February 1969;
the total rain was 220 x 10^3 m^3.



(a) Quantity of rainfall

Using the collector measurements the average rainfall per seeded cloud was at least 160 x 10^3 m^3, there having been some occasions when the aircraft left the cloud before it had stopped raining. From non-seeded clouds the average value was 16 x 10^3 m^3; a ratio between the two categories of about ten times in favour of seeding. Using S to represent seeded occasions and N non-seeded occasions the ranking of clouds in terms of quantity reads:

S S S S S N N N S S N N N N N

Simple permutation theory shows that there is only a 0.005 probability of an arrangement occurring by chance which is equally or more favourable to seeding than this one is (see Appendix B for a more detailed discussion.)

(b) Duration of rainfall

The median rain duration for seeded clouds was 37.5 minutes, and for non-seeded clouds was 12 minutes. In terms of seeding operation the ranking in order of duration is:

S S S N S S S S N S N N N N N N,

which gives a significance level (worked out in the same way as in (a) of 0.002 to support the contention that the seeding prolonged the rainfall. The cloud on the 22nd November has been included in this series, but was not included in the series in (a).

(c) Cloud depth

The average depth of seeded clouds was 4,100 m and of non-seeded clouds was 4,000 m, the difference being small. There was no marked correlation between cloud depth and rain produced (see Appendix C), and the cloud which was the shallowest of the 16 at the moment of selection gave considerable rain after being seeded. However, if it is argued that the difference in cloud depth was the cause of the apparent increase in rain then the deepest cloud, that of 10th February, could be removed from the sequence. This would leave the unseeded clouds slightly deeper, on average, than the seeded ones, and yet the result will still be statistically significant in favour of the seeding. It will be noticed that this deepest cloud ranked only fourth in order of total rainfall and sixth in order of rain duration.

(d) Cloud-top temperature

In Appendix D two experiments are described with clouds whose tops were warmer than $-4^{o}C$, those of 17th February 1969 and 4th March 1969. On those days the cloud yielded hardly any rain.

The Australian single-cloud experiments (Bethwaite et al., 1966) suggested that seeding was effective only if the cloud-top temperature was $-10^{o}C$ or colder. The clouds in Table 1 are too few to establish what the critical temperature is in Rhodesia - most seeded clouds were colder than $-13^{o}C$, according to the morning radiosonde. This includes the second cloud on 15th January 1969 and that of 19th February 1969, whose height readings 10 minutes after seeding, when the silver iodide would have reached cloud top, suggested temperatures colder than $-13^{o}C$. For information on cloud tops between $-4^{o}C$ and $-13^{o}C$ there is only one seeded cloud, that of 14th March 1969, when there was a moderate temperature inversion over Salisbury at the level of $-9.5^{o}C$; it gave hardly any rain.

(e) Other showers in the vicinity of the experiment

Although clouds were not selected unless greater than 8 km from other clouds giving rain, sometimes showers did break out during the experiment, within 8 km of the selected cloud. This happened with all three non-seeded showers giving rain of any quantity. However, of the six substantial falls from seeded clouds (including 22nd November 1968) only two had other showers within 8 km. This suggests that on days with only isolated showers the effect of seeding would be greater than on days with fairly general showers.

Date	Whether seeded	Cloud top A.M.S.L. m	Cloud top temperature °C	Cloud base A.M.S.L. m	Cloud depth m	Seeding level A.M.S.L. m	Duration of rain min.	Nearest moderate to heavy shower km	Total rain at cloud base, $m^3 \times 10^3$ Collector	Total rain at cloud base, $m^3 \times 10^3$ Impactor
22 November 1968	Yes	6 900	−15·5	3 100	3 800	3 100	31	50	Mod/Heavy	Mod/Heavy
13 December 1968	No	6 900	−12	2 500	4 400		2	15	Trace	Trace
20 December 1968	No	7 300	−16·5	2 600	4 700		23	5	69	42
23 December 1968	No	6 500	−10	2 800	3 700		13	3	20	16
2 January 1969	No	6 000	− 7·5	2 600	3 400		46	5	42	29
15 January 1969	No	6 500	− 9·5	3 300	3 200		Nil	80	Nil	Nil
15 January 1969	Yes	5 800	− 6*	3 400	2 400	4 500 /3 400	38	65	80	52
31 January 1969	Yes	7 200	−13	2 600	4 600	4 100	24	25	14	Not available
1 February 1969	Yes	7 300	−14·5	2 700	4 600	4 200	52	15	> 590	Not available
10 February 1969	Yes	7 700	−17·5	2 200	5 500	4 000	37	6	95	88
18 February 1969	No	6 100	− 6	2 400	3 700		Nil	15	Nil	Nil
19 February 1969	Yes	6 100	− 8*	2 900	3 200	4 100	55	25	> 99	> 75
24 February 1969	No	7 200	−15	2 900	4 300		13	10	Trace	Trace
26 February 1969	Yes	7 900	−22	3 200	4 700	4 100	60	5	> 220	> 110
13 March 1969	No	6 700	−10	2 400	4 300		11	80	< 1	1
14 March 1969	Yes	6 700	− 9·5	2 700	4 000	4 100	18	10	3	2

Notes:
1. Cloud tops, bases and temperatures are at the time of selection.
2. Clouds marked * had become colder than −13°C at the top by 10 minutes after seeding.
3. From the beginning of January all cloud-top heights were estimated from a lower altitude using a clinometer compass.
4. At the beginning of February the impactor exposure time was reduced.

Table 1.

Results of experiments

(f) Strengths of updraughts during seeding

The updraughts measured by the aircraft are probably related to the life cycle of the cloud. When the seeding instruction turned out to be "Leave it alone" it did not matter if the cloud had got to the downdraught stage and was just about to rain. A cloud was never selected unless this was judged not to be the case, but sometimes the condition of the cloud changed between selection and seeding. In non-seeded cases where the rain began during the seeding run, downdraughts were usually recorded on the aircraft indicator, but the cloud was retained in the sequence. The only occasion when this happened with a seeded cloud was on 28th December; it began to rain between selecting the cloud from near its top and the first seeding run near the base. Even though substantial rain followed the seeding, one could not really be sure that the silver iodide had reached cloud top and contributed to the rain; nor could the cloud be fairly treated as a non-seeded occasion. This cloud was deleted therefore from the sequence, and thereafter the selection of clouds was made from lower down. In other cases, clouds were accepted which were already giving light coalescence rain but whose tops were not yet glaciated. (Silver iodide stimulates the freezing process, in rain formation, and does not affect the coalescence process.) When these clouds were seeding occasions, updraughts were found in a non-raining section of the cloud, and thus they were accepted.

It is interesting that on all six occasions when substantial rain followed seeding, the updraughts recorded during most or all of the seeding runs ranged from moderate to strong or very strong. Of the other seeded occasions, 31st January 1969 gave very strong downdraughts on one run, and very strong updraughts on the other. On 14th March 1969 the first seeding run gave a fairly strong updraught, but the next three runs yielded no vertical currents of any significance.

These results, admittedly few, suggest that seeding will be more successful if carried out in sustained updraughts in the cloud.

(g) Rain becoming stronger about 25 to 30 minutes after seeding

On four seeded occasions the rain died away and then became markedly heavier again, implying that the seeding rejuvenated the rain-forming process. On 1st February 1969 and 26th February 1969 it became stronger about 23 minutes after the first seeding run (see Figure 4). On 15th January 1969 and 19th February 1969 it became stronger about 25 minutes after the last seeding run, which was about 35 minutes after the first one. (On 15th January rain fell 18 minutes after the first run, but it should be mentioned that the seeding level on that run was at least 300 m higher than on all other occasions.) This is consistent with experience elsewhere, which attributes about 10 to 12 minutes for the silver iodide to reach cloud top, and a further 10 to 15 minutes for the rain to fall to cloud base.

On 22nd November 1968 a number of possible experimental clouds were approached, but collapsed before their top temperature could be measured. When eventually the aircraft was able to measure the temperature of a possible cloud and descend for seeding, rain and light hail fell about 23 minutes after the first seeding run. At the time of selection, the cloud chosen looked no different from the others that had already collapsed without giving rain. On this occasion puddles of water could be seen on the ground as a result of the rain.

CONCLUSIONS

Although few in number, the experiments strongly and consistently suggested that the rainfall at the base of isolated cumulus clouds with tops at about -13°C or colder could be increased by silver iodide seeding. For tops between -4°C and -13°C the number of experiments was insufficient to justify any conclusion. Two clouds with tops warmer than -4°C indicated no significant effect from seeding.

There was also a strong suggestion that the lifetimes of seeded clouds were prolonged by seeding.

There were indications that if sustained updraughts were felt during seeding then the silver iodide was more effective than on other occasions, and that seeding was particularly effective when no other showers developed within 8 km of the selected cloud, but the experiments supporting these two conclusions were too few to justify any statistical treatment.

ACKNOWLEDGEMENTS

The experiments were carried out on the instructions of Brigadier the Hon. A. Dunlop, D.S.O., M.P., Minister of Transport and Power.

The impactor was made by the Instruments Section, and the collector by the Safety Equipment Section of the Royal Rhodesian Air Force. Messrs. Cochrane Sons & Co. (Pvt.) Ltd. made their wind tunnel available to test the rain collector during its development stage. B.A.T. Rhodesia Ltd. supplied the spools of aluminium tape for the impactor.

I am indebted to Messrs. Torrance, Baker, and Swemmer of the Department of Meteorological Services for the construction of the separating chamber.

Invaluable advice on the planning and execution of the experiments was received from Dr. E. G. Bowen's Division of Radiophysics, CSIRO, Sydney, and Dr. E. J. Smith and Dr. E. E. Adderley were particularly helpful.

No. 3 Squadron, RRAF, supplied and piloted the DC 3 aircraft used in the experiments. The aircraft was modified for and maintained during the experiments by the technical staff of No. 3 Squadron.

Messrs. Sinclair, Gordon-Cumming, Withers, Davidge, and Barter assisted with the airborne operations and completed the laborious task of counting and classifying all the raindrops on the impactor tape.

I am grateful to the Director of Meteorological Services for permission to publish this paper.

- - - - -

REFERENCES

Bethwaite, F. D., Smith, E. J., Warburton, J. A., and Heffernan, K. J.(1966). Effects of seeding isolated cumulus clouds with silver iodide. J. Appl. Met., 5, 513-520.

Ostlund, H. G. (1968). Hurricane tritium (Part 2): Air-sea exchange of water in Betsy, 1965. Tellus, 20, 578.

Smith, E. J. (1950). Observation of precipitation with an airborne radar. Austral. J. Sci. Res., A3, 214-223.

Smith, E. J. and Heffernan, K. J. (1968). Some tests on airborne silver iodide burners. J. Appl. Met., 8, 297-299.

- - - - -

APPENDIX A

Formula used in evaluation of rate of rain flow

If the rain distribution $\rho(x,y)$ is assumed to be parabolic along all sections then $\rho(x,p+qx) \equiv Px^2 + Qx + R \quad \forall p,q.$

So $\rho(x,y)$ can only be a second degree polynomial, which by a suitable choice of axes (lengths $2a$ and $2b$) can take the form

$\rho = J\ (1 - x^2/a^2 - y^2/b^2)$

which is an elliptical shower where J, a and b vary with time.

Volume of water V collected in a traverse along Ox

$$V = \int_{-a}^{a} A\rho dx = \frac{4AJa}{3} \quad (A \text{ is the funnel cross section})$$

and similarly along Oy.

$$\text{Rate of flow of rain from cloud} = w \int_{-a^*}^{a^*} \int_{-b}^{b} \rho\ dx\ dy$$

where w represents the vertical fall speed of the rain drops and $a^* = a\ (1 - y^2/b^2)^{\frac{1}{2}}$, which reduces to

Rate of rain flow $= \frac{1}{2}wab\pi J$

(on substituting $y = b \sin\theta$ for the second integration)

$$= \frac{3w\pi Vb}{8A} \text{ using (1).}$$

APPENDIX B

Significance tests on ranking

(a) Quantity of rainfall

S S S S S N N N S S N N N N N (15 clouds)

Probability of this arrangement appearing $= \dfrac{7!\ 8!}{15!}$

Sum of ranks of *S*'s = 34

Total number of possible arrangements where sum of ranks of seeded clouds is 34 or less = 30

(The lowest possible rank for a seeded cloud under this condition is 13th.)

Therefore significance level $= \dfrac{30 \times 7!\ 8!}{15!} = 0.0047.$

(b) Duration of rainfall

S S S N S S S S S N S N N N N N N (16 clouds)

Probability of this arrangement appearing $= \dfrac{(8!)^2}{16!}$

Sum of ranks of *S*'s = 42

Total number of possible arrangements where sum of ranks of seeded clouds is 42 or less = 30

(The lowest possible rank for a seeded cloud under this condition is 14th.)

Therefore significance level $= \dfrac{30 \times (8!)^2}{16!} = 0.0023.$

APPENDIX C

Correlation between cloud depth and rainfall

Using an estimated value of 100×10^3 m^3 for the rainfall on 22nd November 1968, the linear correlation r between cloud depth and rainfall is just under + 0.25.

A 't' test can be applied to see how significant this correlation is. With 16 clouds, the value of

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} = 0.95.$$

With 14 degrees of freedom, the t table shows that such a correlation, of either sign, would occur by chance on 36% of occasions. The positive correlation would occur on 18% of occasions, showing that it is not particularly significant.

APPENDIX D

Clouds not included in the statistical sequence but useful for other experiments

21 November

It is possible that if silver iodide is put into a cloud at the –10°C level, instead of at the base, then the seeding is more effective, although there have been reports to the contrary. It was intended that a few such experiments be done in our programme on single clouds, and a cumulus cloud reaching to 6 100 m (–11°C) was seeded near its top on 21st November 1968 (it was not suitable for base seeding, because the sky was covered in a layer of thick altostratus). However the cloud collapsed within 20 to 25 minutes. The icing on the aircraft was very bad in cloud at that level, and it was evident that top-seeding was impractical.

19 December

A cloud with a very poor base was seeded well above the base at about 4 700 m (approximately 0°C). Its top was estimated to be about 6 900 m. Strong updraughts were felt at the chosen level of 4 700 m during seeding. Substantial rain followed, visibly heavier than any other in the vicinity.

20 January

A cloud with a very poor base was seeded between the base and freezing level. Strong updraughts were felt during seeding, and the cloud yielded heavy rain.

21 January

Again the only available clouds were with unacceptable bases, so an attempt was made to seed at the base, instead of higher up as in the two previous clouds. Hardly any updraughts were felt during seeding, but fairly heavy rain followed. However this cloud was at least 1 500 m deeper than those on 20th January and 19th December.

17 February

A cloud whose top was at 5 800 m (–5.5°C on the radiosonde), was seeded, but updraughts ceased to be felt within five or six minutes of seeding. A second height estimate using the clinometer compass was made about 12 minutes after seeding (when the silver iodide would have reached cloud top), and these confirmed the collapse of the cloud to 5 500 m (–3.5°C). By 15 minutes after seeding the apparent level of the top was about 4 700 m, much warmer than the necessary –5°C. The cloud was therefore not included in the sequence. It gave only 1.0×10^{3} m³ of rain.

3 March

A cloud with an unacceptable base, and surrounded by a thick layer of altocumulus and with another shower within 5 km of it was seeded, and gave fairly heavy rain, but merged with the other shower before sufficient measurements could be taken.

4 March

Two cumulus cells 2 km apart were seeded in one operation, the younger one being included by accident. Both gave a little rain, but the compass readings on the primary, when worked out later, suggested a top temperature of only about –3.5°C. (Readings were available only before seeding, not after.) The primary cell yielded 10×10^{3} m³ and the secondary 22×10^{3} m³ of rain.

We were thus able to demonstrate the possibility of measuring the rain from two cells simultaneously.

APPENDIX E

Relationship between collector and impactor

The impactor was used on the strength of having been used successfully elsewhere for quantitative rain measurement in a similar experiment. In addition it provides a record of the drop spectrum, and an independent estimate of the length of time in rain, which is necessary for the calculation of total rainfall but is not easy to measure from inside the aircraft. Its reliability enabled an assessment of whether or not the collector could be used as an independent rain-measuring instrument. There were in fact two clouds where the instruments disagreed as to the ranking order of total rainfall, but both were seeded clouds which gave substantial rain, and the conclusions would apply therefore to both.

The impactor rainfall estimates were based on three independently made counts of the number and sizes of drop imprints. Comparisons of measurements made by the two instruments on individual runs indicated a definite tendency for the ratio, *collector rain intensity estimate/impactor rain intensity estimate,* to increase as the rain became heavier.

Heavy rain contains more drops and probably a higher proportion of large drops than light rain. This leads to more overlapping of imprints on the impactor tape, and an underestimate of heavy rainfall by this instrument. The collector will scoop up most of the large drops, but is liable to lose some of the smaller ones in the flow which is forced to by-pass the collecting ring by the tapering of the funnel. This would cause the collector to underestimate in light rain, but because the small drops in a shower would tend to evaporate on the way to the ground the collector estimate of total rainfall would be biased towards the value on the ground, as distinct from the rain value at cloud base, the farmer being more interested in the first of these.

An increase in aircraft speed sometimes gave a higher value of the ratio, *collector rain intensity estimate/impactor rain intensity estimate*, and sometimes a lower value. At least this is comforting, because if there had been a consistent relationship between changes in the aircraft speed and changes in the ratio of rainfall estimates then one would have been forced to conclude that there was serious distortion of the collector estimate (probably as a result of the aircraft slipstream rather than of the tapering of the funnel).

The collector samples a volume which is 500 times greater than that sampled by the impactor. Also, besides giving a better estimate of heavy rain than the impactor, its measurements are less subjective and much less time-consuming to evaluate. On a few individual runs when the co-pilot's impression of the rain on the windscreen was available, and the collector and impactor reading differed appreciably, the co-pilot's impression supported the collector. (These impressions were too subjective to use as a primary means to an evaluation.)

During individual runs, the collector's rain intensity estimate was higher than the impactor estimate if the rain was heavy, but lower if the rain was light. Sometimes the collector estimate was even double the impactor one, and sometimes only half of it. With the earlier impactor design (exposure time 0.6 s in 6.25 s) the two estimates were equal when the water collection rate was about 6 cm^3 per minute. When the impactor exposure time was reduced to 0.35 s in 6.25 s, this critical rate increased to about 16 cm^3 per minute in the collector.

The collector enables an immediate assessment, from inside the aircraft, of the water content of the cloud during seeding and during rain-measurement. (It has been explained how the first of these was useful in deciding when to descend to cloud base.) It would also enable chemical analyses to be made of the silver iodide content of the rain before seeding, immediately after seeding, and 30 minutes after seeding.

If used together with the collector in a series of single cloud experiments, the impactor would probably be more use if left open all the time, but redesigned so that the tape moved more quickly than at present. It would then provide a more accurate measure of the length of time in rain than it does now (there is an error when the shutter is closed at the time of entry into or exit from the rain) and also there would be more occasions than is the case now when the intensity variations recorded on the tape really did represent peaks and troughs in the shower profile.

AN AREA CLOUD SEEDING EXPERIMENT IN THE NORTH OF RHODESIA, 1970-71

D. L. McNaughton

Department of Meteorological Services
Causeway, Salisbury

SUMMARY

A cloud seeding experiment was conducted in a region north-west of Salisbury, in which selected clouds over a defined target area were either seeded with silver iodide smoke from an aircraft, or merely observed, according to randomized instructions. Comparisons of the subsequent rainfall in the target area with the rainfall in control areas which were never seeded indicate that the seeding had a positive effect. There was also some evidence that rainfall was higher on days after seeding.

Subsidiary experiments with isolated cumulus cells indicate that silver iodide has no effect on clouds whose tops are warmer than -10°C.

INTRODUCTION

Experiments conducted in 1968-69 on single cumulus cells demonstrated that the seeding with silver iodide of selected isolated clouds caused a substantial increase in the rain that they produced at cloud base (McNaughton, 1970). It was logical to proceed to an area experiment in order to investigate whether this increase showed at ground level, and eventually to attempt to assess the actual rainfall increase, in inches, when averaged over a specified area.

Cloud seeding seems to prolong the lifetime of the cloud besides increasing its rainfall (Bethwaite, Smith, Warburton and Heffernan, 1966; McNaughton, 1970) and it therefore almost certainly causes the rain to be distributed over a greater area. The experimental area should be considerably larger than that traversed by one seeded cloud, because it might be queried whether the increase in its rainfall is at the expense of neighbouring clouds.

FACILITIES

No. 3 Squadron of the Rhodesian Air Force provided the crew and the same DC-3 aircraft used in the 1968-69 programme; the silver iodide burner used was also the same. The solution used consisted of four parts of silver iodide and one of sodium iodide all dissolved in about 50 parts of acetone, all by weight. A vortex thermometer, for which no thermodynamic correction is necessary, was mounted on top of the aircraft and measured the outside air temperature; this helped in the selection of clouds, when used in conjunction with clinometer compass readings of the cloud tops taken from the aircraft. Dawn radiosondes were sent up from Salisbury every day, and enabled an independent estimate to be made of the temperature at aircraft flight level.

Extra raingauges were installed to the west and north-west of Salisbury in order to provide an increased coverage of rainfall reports, aiming at a density of one raingauge per 50 km^2.

EXPERIMENTAL DESIGN

Layout of Areas

Experience gained in 1969-70 showed that a two-target design could not be fitted into the region with the extra raingauges without making the individual targets so small that it was difficult to find suitable clouds in them. It was therefore decided to have just one large target area, T, in 1970-71, which would be randomly seeded or left alone. The sizes of the various test areas and the numbers and distributions of the raingauges in them are shown in Figure 1.

The experiment was suspended whenever the winds governing the cloud movement lay between 270°and 360°, unless the windspeed was less than 5 knots. The main control area C_m was thus completely free from contamination from clouds coming from the target area. On some days the north and south controls did lie downwind of the target, but were not used in the analysis of the rainfalls of those days.

Time Units

It was decided to assign the same seeding instruction to every day in any given week, from Monday to Friday. This was because cloud seeding experience in Australia (Bowen, 1966; Smith, 1967) has suggested that experiments which change their seeding instruction every day have a smaller chance of success than experiments with longer time units, possibly because the effect of seeding on one day is carried over into subsequent days. The physical cause of this is not known, but it is more likely to be a result of extra water having been brought to the ground than of silver iodide remaining in the atmosphere; one possibility is that rain stimulates greater transpiration, which in its turn stimulates further rain.

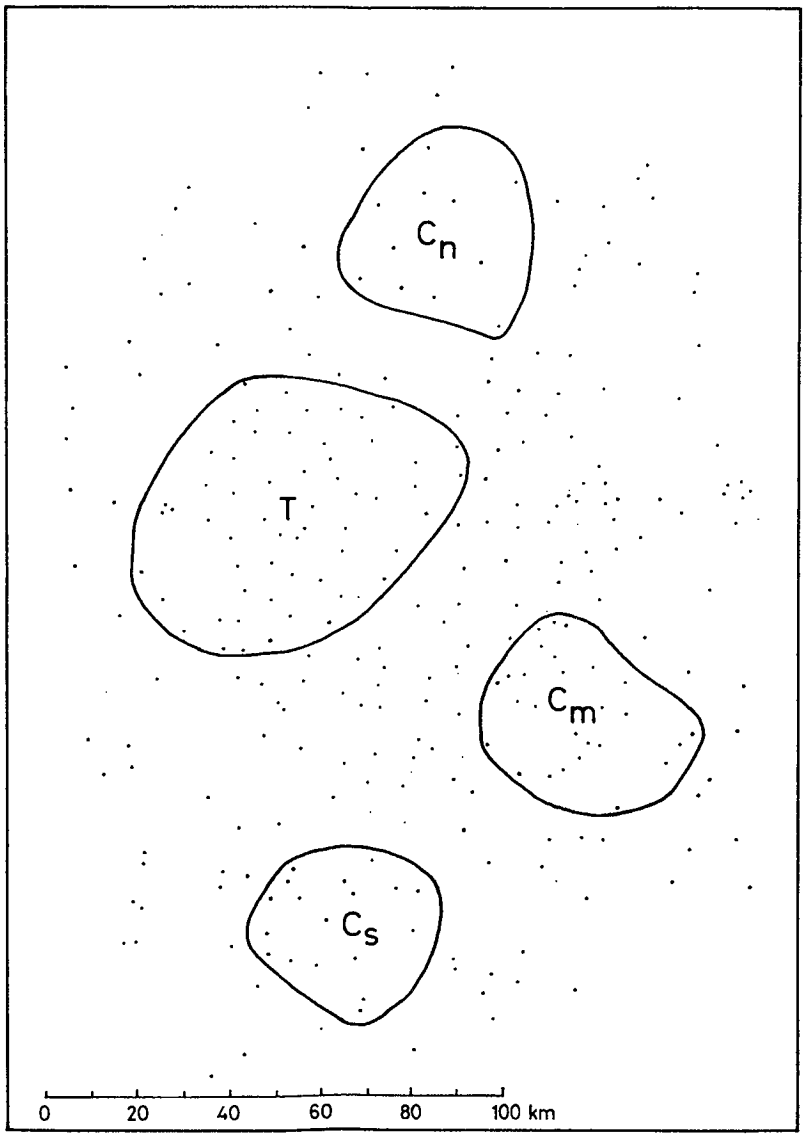
The Central Statistics Office supplied a random sequence consisting of one of the two alternatives "seed" or "leave", enabling one of these instructions to be assigned to each week of the rainy season. The experiment was suspended during the week-end to allow the decay of the persistence effect of seeding, if one existed.

EXPERIMENTAL PROCEDURE

Selection of Days

A separate decision whether or not to fly was made for every weekday in the season. There was no flying unless the clouds were likely to reach the -10°C level in the atmosphere, because experiments in Australia (Bethwaite et al., 1966) have suggested that seeding might decrease the rainfall yield if the cloud-top temperature is warmer than this. There was also no flying when

FIG. 1—TEST AREAS AND RAINGAUGE NETWORK, 1970–71, IN AN AREA TO THE NORTH-WEST OF SALISBURY
T = Target, C = Controls



there was widespread heavy rain over the test areas; flying was undertaken only if convective cloud development seemed likely.

Forecasts of afternoon cloud tops were made each morning using a adaptation of the cumulus model P used in Florida (Simpson and Wiggert, 1971). This involved computing the buoyancy of a developing cloud, at successive levels in the atmosphere, after allowing for entrainment and precipitation, and then plotting on the tephigram its probable path curve up to the level where its vertical velocity became zero.

Selection of Clouds

The selection of cumulus clouds over or just upwind of the target area took place at about 14000 or 15000 ft asl. From the beginning of December the clinometer compass was used to obtain angles of elevation of cloud top, as during the 1968-69 season (McNaughton, 1970), except that readings were taken at 30-second intervals, enabling the cloud height to be estimated immediately using prepared tables, which were carried in the aircraft. This made it possible to avoid seeding clouds whose tops had not reached the -10°C level, which was usually about 7000 ft above the aircraft, too high for a purely visual estimate to be reliable. Another set of tables, making use of the times of entry into and exit from the cloud, enabled a retrospective check to be made of the cloud-height estimate.

In addition suitable clouds had to be solid in appearance, still growing, and not yet glaciated.

Seeding and Rain Measurement

Each cell selected was usually given two seeding traverses, and then the aircraft went in search of other suitable clouds. If no significant updraughts had been felt during seeding, however, and no other clouds could be seen in the target, then two more seeding runs were flown in this same cloud in search of the necessary upcurrents. During non-seeding weeks the procedure was the same as for seeding occasions, except that the burners were not switched on.

Two hours was a typical time spent by the aircraft in the area. When there appeared to be no further clouds suitable for seeding the aircraft would descend to cloud base to observe the rain. Whenever possible, measurements were taken in the rainfall collector (McNaughton, 1970); sometimes ice became clogged in its tubes, making readings impossible..

The raingauges in the test areas were read at 8 a.m. every day, and the figures were processed at Meteorological Headquarters by people who did not know which were the seeding or non-seeding weeks.

Supplementary Experiments on Single Clouds

If no suitable clouds were available in the target area then isolated cumulus clouds were sought elsewhere, to see whether the successful 1968-69 experimental results could be repeated. Care was taken to choose these far enough away from the target and controls so as not to interfere with the area experiment.

Description of the Experiment on 5 February 1971

This was one of the busier and more rewarding days, and therefore serves to illustrate many aspects of the experimental procedure.

At 8 a.m. there had been reports of early morning rain to the north and west of the target area, but not over the target itself. The Belvedere radiosonde showed two nearly saturated layers at 11000 feet and 15000 feet asl, with slightly drier air above; at 19000 ft the dewpoint depression was $7^{o}C$, and at 25000 ft it was $13^{o}C$. Between 17000 ft and 20000 ft the temperature trace showed the atmosphere to be conditionally unstable.

The first cloud was selected in the west of the area at 2:40 p.m. Clinometer compass readings indicated a top two or three degrees warmer than the necessary $-10^{o}C$, and therefore the burners were not switched on, even though it was a seeding week. When the clinometer readings were used in conjunction with the times of entry into and exit from the cloud, however, they gave a height estimate which was virtually on the $-10^{o}C$ level, 21000 ft. This was confirmed by the readings on the second run approximately eight minutes later, and the burners were therefore turned on. Three seeding traverses were carried out, during which moderate updraughts were felt, becoming stronger by the third run. The top height estimate on this last traverse, 20 minutes after the cloud had been selected was 26000 or 27000 ft asl; heavy rain was also encountered during this run, with 0.24 inches measured in the collector in 80 seconds.

A second cloud was selected in the southwest corner of the area; its top was estimated as 20 or 21000 ft and it was seeded. The times of entry and exit suggested that it had not quite reached the $-10^{o}C$ level, however, and it collapsed, giving no rain.

The aircraft then returned to the first cloud, which had attained 30000 ft asl; it was now 40 minutes since its first seeding run. The cloud was raining, but because it still showed signs of active growth it was given one more seeding run.

A third cloud in the north-west of the target area, top about $-12^{o}C$ (22000 ft), was given two seeding runs, which were accompanied by fairly good updraughts; these were followed by light to moderate rain.

The total silver iodide burning time amounted to 18 minutes, on this particular day, of which 8 minutes were given to the first cloud.

RESULTS

Of 110 programmed days during the season, 66 were selected for flying, and 36 actually flown. Of these 24 yielded at least one suitable cloud in the target area; 13 of the 24 were seeding days and 11 were non-seeding. Five other flying days were used for single cloud experiments, and so only seven sorties out of the 36 were completely abortive.

Table 1 shows the rainfalls from the 24 days on which the area experiment took place. Four combinations of controls were used, taking the main control first by itself, then together with the north, then with the south, and finally with both the north and the south controls. The rainfalls presented were taken as the arithmetic means of the readings from all raingauges in the area or composite area. The list of main-plus-north control area rainfalls does not include occasions when the north area was downwind of the target, and similarly when the south control lay downwind; both types of days were deleted from the list of rainfalls averaged over all three controls.

The apparent increase in rainfall, due to seeding, is given by the double ratio:

$$\frac{\Sigma Ts/\Sigma Cs}{\Sigma T_N/\Sigma C_N}$$

where T and C refer to target and control rainfalls respectively, and the subscripts S and N to seeding and non-seeding weeks. The apparent increases using each of the various combinations of controls are shown in Table 2; each method suggests a substantial positive effect of seeding, but they do not agree as to the amount.

In general the days with the longest burning times (apart from 24 November) are also the days with the highest target-to-control rainfall ratios.

Significance Test

In order to investigate whether or not it was purely due to chance that the highest target-to-control ratios occurred during the seeding weeks, ratios of target rainfall to control rainfall were computed for each weekly random time unit, and the ratios then arranged in descending order.

Denoting seeding weeks by S and non-seeding weeks by N, the order is as follows:

Using main control only: S S N S S N N S S N S S N N N

Using main and north: S N S S S N S S N S N N N N

Using main and south: S S N S S N N S S N S N N N

Using all three controls: S N S S S S N S N N N N N

It will be noticed that in each case more S.s occur in the first half of the sequence than in the latter half, which contains the majority of N.s. Ranking tests (Mann and Whitney, 1947) were applied to each of these sequences to determine the probability of obtaining, purely by chance, arrangements at least as favourable to seeding as those above. In every case this probability is less than 10 per cent, and with two out of the four sequences it is as low as 2 or 3 per cent.: the values obtained are listed in Table 2. An example of a Mann-Whitney calculation is given in the Appendix.

TABLE 1.—AREA RAINFALLS 1970–71

All rainfalls are in mean inches per raingauge

Date	Seeding instruction	Burning time, min	Target rainfall	Control rainfalls			
				Main	Main & North	Main & South	All three
24/11	Seed	28	0,795	0,969	0,770	0,742	0,645
1/12	Leave	—	0,350	0,157	0,407	0,107	0,304
2/12		—	0,048	0,022	0,043	0,015	0,032
10/12	Seed	26	0,094	0,013	0,019	0,009	0,014
16/12	Leave	—	0,031	0,006	0,081	0,004	0,060
21/12	Leave	—	0,080	0,210	0,153	0,173	0,138
1/1	Seed	11	0,161	0,131	0,137	*	*
15/1	Leave	—	0,137	0,257	0,244	0,264	0,253
29/1	Seed	21	0,136	Nil	*	Nil	*
1/2	Seed	24	0,385	0,032	0,279	0,033	0,218
5/2		18	0,209	0,048	0,094	0,032	0,071
11/2	Leave	—	0,806	0,835	0,719	1,109	0,963
12/2		—	0,397	0,354	0,280	0,368	0,310
15/2	Seed	12	0,346	0,094	0,161	0,064	0,121
16/2		10	0,514	0,409	0,363	0,323	0,307
22/2	Leave	—	0,060	0,014	0,014	0,009	0,011
24/2		—	0,066	0,001	0,084	0,001	0,063
25/2		—	0,073	Nil	0,007	Nil	0,005
1/3	Seed	25	0,194	0,003	0,085	0,002	0,062
3/3		13	0,090	0,264	*	0,307	*
4/3		10	0,016	0,259	0,181	0,181	0,141
5/3		13	0,019	Nil	0,021	Nil	0,015
11/3	Leave	—	0,003	0,124	0,086	0,093	0,073
18/3	Seed	28	0,095	Nil	0,059	Nil	0,043

* Denotes rainfalls not listed because one control was downwind of the target.

TABLE 2.—RESULTS OF AREA SEEDING 1970–71

Controls used for comparison	Seeding days		Non-seeding days		Apparent percentage increase in rainfall	Significance level
	Rainfall inches totals*	Ratio T/C	Rainfall inches totals*	Ratio T/C		
Main only . . .	T 3,054 C 2,221	1,375	T 2,050 C 1,980	1,035	+33	0,09
Main and North . .	T 2,828 C 2,167	1,305	T 2,050 C 2,117	0,968	+35	0,03
Main and South . .	T 2,893 C 1,692	1,710	T 2,050 C 2,142	0,957	+79	0,05
All three controls .	T 2,667 C 1,636	1,630	T 2,050 C 2,210	0,927	+76	0,02

* T denotes target area rainfall in inches; C denotes composite control area rainfall in inches.

Assessment of the Extra Rainwater

The mean rainfall in the target area, when summed for the 13 seeding days, amounted to 3.05 inches. Table 2 shows that, using only the main control area for comparison, the extra rain due to seeding was 33 per cent over and above the natural rainfall. The natural rainfall was therefore 2.29 inches, and the apparent artificial increase was 0.76 inches, taken over the target as a whole.

The size of the target area was 2,763 km^2, estimated by planimetering the map. However, only a proportion of the whole target area received rain which could be directly attributed to seeding. This proportion can be conveniently called the "area of benefit." From detailed plots of individual station rainfalls, it is estimated that the area of benefit averaged approximately 400 km^2.

The 0.76 inches increase distributed over the whole target area averaged 0.06 inches per seeding day. Considering more specifically the area of benefit, the estimated average increase per seeding day was approximately

$$\frac{0.76 \times 2763}{13 \times 400} = 0.40 \text{ inches.}$$

This is probably a conservative estimate of the extra rainwater.

The yield in the area of benefit may also be calculated using the more favourable target-control comparisons. From the data on the ten seeding days when the target area was compared with all three control areas, the yield due to seeding is estimated at a 76 per cent increase. On this basis the average increase of rain per seeding day in the area of benefit works out at 0.79 inches.

Whilst the yield in the actual area of benefit is comparatively substantial, it is not possible to predict where the area of benefit will be within the target area.

The Short-Term Persistence Effect of Seeding

It has been explained above that the choice of the week as the time unit, instead of the day, was based on experience in Australia. In order to investigate whether or not similar conditions prevail in Rhodesia, target-to-control rainfall ratios were examined on the first, second and third days after every seeding flight to see whether they showed any signs of increased rainfall. These days were treated as quasi-seeding days, so that control areas which lay downwind of the target on those occasions were excluded from the analysis.

"Persistence days" sometimes fell in the middle of the week, not only on the weekends; sometimes there were as many as six such days pertaining to just one seeding week. Nothin would have been gained, statistically, by treating each set of three days as one unit, because they would not have been random; each day was therefore taken separately, in order to provide a larger population. Even though these units are not, strictly, part of a random distribution it was decided to compare them with the flying days from non-seeding weeks, also taken singly, and to apply a Mann-Whitney ranking test.

TABLE 3.—SINGLE CLOUD EXPERIMENTS IN 1970–71

Date	Cloud top when selected ft a.s.l.	Whether seeded	Seeding level ft a.s.l.	Max. updraught during seeding ft/min	Max. cloud top attained ft a.s.l.	Coldest temperature attained °C (radiosonde)	Rain (Max. collector reading)
20/11/70	20 000	Yes	14 500	1 000	20 000	−8	Nil
3/2/71	20 000	Yes	16 200	300	20 000	−8	Nil
5/2/71	20 500	Yes	17 200	500	20 500	−9	Nil
12/2/71	19 700	Yes	15 700	800	19 700	−7	Nil
7/12/70	21 000	Yes	12 500	800	26 000	−18	Heavy*
3/2/71	23 000	Yes	16 300	900	24 000	−13½	Heavy (>0,30″ in 50 s)
5/2/71	21 000	Yes	17 200	1 000	>30 000	<−25	Heavy*
18/2/71	20 500	Yes	15 200	300	>30 000	<−25	Heavy (0,29″ in 87 s)
2/3/71	24 000	Yes	14 800	1 100	>30 000	<−25	Heavy (0,33″ in 45 s)
11/3/71	23 000	No	(16 100)	(600)	23 500	−14½	Light (0,06″ in 65 s)

* Icing prevented accurate measurements on these occasions.

Some of the ratios were infinite, and these were arranged in order of the absolute magnitude of the target rainfall.

If non-seeding days are denoted by N, and persistence days which were not also seeding days by P, then the following one-sided significance levels and rankings of target-to-control ratios are obtained:

Main control only: significance 0.13

P P N P N P P P N P P N P P P P N N P P N P P N P N N P N

Main and north: significance 0.08

P N P N P P P P P P P N P N N N P N P N N N P P N

Main and south: significance 0.14

P N P P N P P P N P N P P N P N P P P P P P N P N N N P N

All three controls: significance 0.06

P N P N P P P P P P P N N P N N P N N N N P P N

The evidence certainly suggests that if we had made our random time unit the day instead of the week, then the positive effect of the seeding would have been disguised.

Supplementary Experiments on Single Clouds in 1970-71

Instead of randomly seeding or leaving the clouds alone, as in 1968-69, it was decided that every single-cell experiment in 1970-71 would be seeded, in order to try to establish the critical temperature in Rhodesia above which silver iodide does not stimulate rain. In Australia this temperature appears to be about -10°C (Bethwaite et al., 1966).

Data on the 1970-71 single clouds appear in Table 3; a few of these were actually in the target and were part of the area experiment. Four experiments, including the one on 5 February which has been described above, indicate that Rhodesia's critical temperature is not warmer than Australia's -10°C. Five other experiments with clouds colder than -10°C are consistent with the 1968-69 results in that they produced substantial rain after being seeded. On 3 February the cloud eventually merged with another cell, initially smaller than itself, and the merger seemed to rejuvenate the rain; American experiments also suggest that the amalgamation of two cells is conducive to greatly increased rainfall (Simpson and Woodley, 1970).

Table 3 also contains details of a single cloud which was not seeded because it was part of the area experiment in a non-seeding week. In spite of attaining 23500 ft (-14½°C) it gave only very light rain.

CONCLUSIONS

Although few in number, the experiments indicate that the seeding with silver iodide of clouds over a defined target area increased the rainfall by a substantial amount, if compared with the target rainfall on non-seeding days and with the rainfall in control areas which were never seeded.

Other experiments with isolated cumulus cells indicate that silver iodide does not stimulate rain if the cloud top does not penetrate the $-10^{o}C$ level in the atmosphere; seeding may even have a negative effect. Experiments with clouds colder than $-10^{o}C$ at the top confirmed the 1968-69 conclusions that seeding increased their rainfall yield.

ACKNOWLEDGEMENTS

I am grateful to the Director of Meteorological Services for permission to use, in this paper, the material contained in the Departmental Report on 1970-71 Cloud Seeding, Series A, No. 35.

This experiment comprised the third programme of cloud seeding experiments carried out by the Rhodesian Department of Meteorological Services. The Meteorological Department provided the airborne technical crew and processed the rainfall data from the ground stations. I am also indebted to other colleagues in the Department for help with the many other aspects of the experiment.

Without the ready cooperation of the aircrew and ground crew of No. 3 Squadron of the Rhodesian Air Force the experiments would not have been possible.

Invaluable advice on the planning, execution and evaluation of this experiment was received from Doctors E. G. Bowen, E. J. Smith and E. E. Adderley of the Division of Radiophysics, CSIRO, Sydney.

The tables of clinometer readings and cloud heights were compiled using the Hewlett-Packard computer at the Hydrological Branch, Ministry of Water Development, where Mr. P. B. Mitchell provided the necessary programme.

- - - - -

REFERENCES

Bethwaite, F. D., Smith, E. J., Warburton, J. A., and Heffernan, K. J., 1966. Effects of seeding isolated cumulus clouds with silver iodide. J. Appl. Met. 5: 513.

Bowen, E. G. 1966. The effect of persistence in cloud seeding experiments. J. Appl. Met.5: 156.

Mann, H. B. and Whitney, D. R. 1947. On a test of whether one of two random variables is larger than the other. Ann. math. Statist. 18: 50.

McNaughton, D. L. 1970. Seeding single cumulus clouds in Rhodesia with silver iodide; 1968-69. Proc. Trans. Rhodesia Sci. Assoc. 54(2):85.

Simpson, J. and Wiggert, V. 1971. 1968 Florida cumulus seeding experiment; numerical model results. Mon. Weath. Rev. U.S. Dep. Commerce. 99:87.

Simpson, J. and Woodley, W. L. 1970. Results of 1970 tropical cumulus seeding program and future plans. Interagency conference on Weather Modification, Virginia Beach, U.S.A., 199-228.

Smith, E. J. 1967. Cloud seeding experiments in Australia. Proc. Berkeley Symp. Math. Statist. Probab. 5:161.

- - - - -

APPENDIX

MANN-WHITNEY TEST

Using just the main control area, the ranking is

S S N S S N N S S N S S N N N

Total number of units $n = 15$

Number of seeded units $n_1 = 8$, and non-seeded $n_2 = 7$

Sum of the ranks of the 8 S.s $R_1 = 52$
and of the 7 N.s $R_2 = 68$

Total number of times that an N precedes an S $U_{21} = 16$
and that an S precedes an N $U_{12} = 40$

These may be checked using the identities:

$$R_1 + R_2 = \tfrac{1}{2}n(n+1)$$

$$U_{12} = n_1n_2 + \tfrac{1}{2}n_1(n_1+1) - R_1$$

and similarly for U_{21}

$$U_{12} + U_{21} = n_1n_2$$

Mean number of precedences $\bar{U} = \tfrac{1}{2}n_1n_2 = 28$

and variance $\sigma^2 = \dfrac{n_1n_2(n+1)}{12} = 74{,}7$

It is assumed that the variate $\dfrac{\text{mod}(U - \bar{U}) - \frac{1}{2}}{\sigma}$ is normal

$$\frac{U_{12} - \bar{U} - \frac{1}{2}}{\sigma} = \frac{40 - 28 - \frac{1}{2}}{8{,}64} = 1{,}331$$

The position of this value in the normal distribution is such that the probability of obtaining a higher value by chance is 0,09.

RESULTS FROM A 7 YEAR CONTINUOUS SEEDING WITH A GROUND GENERATOR ON THE FRENCH ATLANTIC COAST

Jean Dessens
Jean-Pierre Lacaux

Centre de Recherches Atmospheriques de Campistrous
Observatorie du Puy de Dome, Universite de Clermont

ABSTRACT

A cloud seeding experiment is conducted in Mimizan, France, in a typical marine climate. Silver iodide smokes have been released continuously since 1965 from a ground-based generator located at 6 km from the Atlantic Coast.

The examination of rainfall shows an increase up to 15% in an area of about 800 km^2 centered at 40 km downwind from the generator. It is suggested that sea breeze and valley wind are likely convenient for convective clouds seeding.

1. INTRODUCTION

An experiment of cloud seeding with silver-iodide smoke released from a ground generator is conducted in MIMIZAN, FRANCE, with the purpose to increase precipitation in the downwind area.

MIMIZAN ($44^{o}12'N$, $1^{o}14'W$) is located at 6 km from the Atlantic Coast, in front of the Bay of Biscay. The climate is strictly a marine climate, with prevailing west winds. The terrain is flat, with only coast-dunes of some 40 m high; downland, the level is gently rising up to about 100 m at 70 km from the coast. Nearly the whole land is planted with pines: the French name of this country is "Les Landes".

There is enough rain in this area all over the year, nevertheless more rain allows to give more fertilizer to the forest, which furnishes wood supplying the kraft mill of Mimizan. The artificial rain project has been running from 1965 with the financial support and the technical assistance of the Society "Les Papeteries de Gascogne".

2. EXPERIMENTAL PROCEDURE

The most straightforward method for the delivery of the seeding material is used in this experiment: a ground based silver-iodide generator, located in Mimizan, is continuously running all the year, night and day, except in high-pressure systems, with absolutely no rain cloud for several

days (DESSENS, 1968). The generator is an acetone vortex-generator burning 9 g/h of AgI, with a measured output of 5×10^{16} ice nuclei per hour at $-21^{o}C$ (DESSENS and PHAM VAN DINH, 1968); it is operated by remote control (SAUVAGEOT and DESPAUX, 1970).

Table 1.

Silver Iodide Released

Year	1965	1966	1967	1968	1969	1970	1971
AgI, kg	*	31	71	42	42	60	50

(*: Not noticed, but same order as following years)

Precipitation measurements are obtained from the gauges network of the "METEOROLOGIE NATIONALE". Fourteen additional precipitation gauges are now maintained for the control of the project, but their data are not used in this paper because of the lack of historical data.

3. CONTROL AND TARGET AREAS

Figure 1 gives the mean annual rainfalls around MIMIZAN for the non-seeding period (1954-1964) and for the seeding period (1965-1971) with the corresponding isohyets. There is a strong evidence for a positive effect on the amount of precipitation downwind of the generator, but the problem for a statistical analysis is to decide "a posteriori" what was the target area and what are the control areas.

The following design was used to determine these areas. With the annual rainfalls measured in the 16 gauges, 120 double-mass curves were drawn and classified as follows (Table 2) by computer (LACAUX, 1973):

- There is no significant slope change on the curve (= in Table 2).
- There was a significant change of the slope in 1965, and the new slope continues to 1971 (+ or -).
- There is no conclusive result (Δ).

With this stratification, the 16 gauge stations can be classified in four groups:

- Stations n^{o} 1, 2, 4, 5, 6, 7, 9, 10, 11, 13: no change in rainfall between these stations.
- Stations n^{o} 8, 14, 15, 16: increase in rainfall for the seeded period.
- Station n^{o} 3 (Biscarosse): unexpected decrease of rainfall from 1965. No explanation offered.
- Station n^{o}12 (Pissos): no conclusive result.

Table 2.

Variations of the Relative Rainfalls in the Seeded Period Between the 16 Gauge Stations

Gauge Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Arcachon		=	=	=	=	=	=	-	=	=	=	=	=	-	-	-
2. Arengosse	=		=	=	=	-	=	-	=	=	=	-	=	-	-	-
3. Biscarosse	=	=		-	-	-	-	-	-	-	-	-	-	-	-	-
4. Budos	=	=	+		=	=	=	-	=	=	=	=	=	-	-	-
5. Captieux	=	=	+	=		=	=	-	=	=	=	-	=	-	-	-
6. Cazaux	=	+	+	=	=		=	-	=	=	=	Δ	=	-	-	-
7. Contis	=	=	+	=	=	=		-	=	=	=	=	=	-	-	-
8. Labouheyre	+	+	+	+	+	+	+		+	+	+	+	+	=	=	=
9. Labrit	=	=	+	=	=	=	=	-		=	=	=	=	-	-	-
10. Le Teich	=	=	+	=	=	=	=	-	=		=	=	=	-	-	-
11. Mimizan	=	=	+	=	=	=	=	-	=	=		-	=	-	-	-
12. Pissos	=	+	+	=	+	Δ	=	-	=	=	+		=	-	-	-
13. Sarbazan	=	=	+	=	=	=	=	-	=	=	=	=		-	-	-
14. St-Symphorien DFCI	+	+	+	+	+	+	+	=	+	+	+	+	+		-	-
15. St-Symphorien EF	+	+	+	+	+	+	+	=	+	+	+	+	+	=		=
16. Ychoux	+	+	+	+	+	+	+	=	+	+	+	+	+	=	=	

Example: Rainfall at n°6 (Cazaux) remains in linear relation (=) with rainfall at n°1 (Arcachon), n°4 (Budos); increases (+) from 1965 comparatively with rainfall at n°2, n°3; decreases (-) comparatively with rainfall at n°8, n°14 . . . ; there is no conclusive comparison (Δ) with n°12.

The choice of the control areas must then be the following: (i) Target Area, or more properly, "Affected Area": station n°8, 12, 14, 15, 16 (for geographical consideration n°12 must be included in this area).

(ii) Control Area: for similarity, it must be composed of five stations of the first group. Various arrangements have been tested, with similar results in the subsequent statistical analysis. In this paper, we consider a "Compound Control Area" with five stations regularly located around the "Affected Area". Figure 2 settles the boundaries of the areas respectively affected and not affected.

4. EVALUATION OF THE RAINFALL INCREASE IN THE AFFECTED AREA

Table 3 gives the values of the rainfall totals for the groups of 5 stations in the Affected Area and Control Area, for the seeded and unseeded years.

Table 3.

Rainfall Totals (in mm) in the Two Areas

Year	Unseeded Target	Control	Year	Seeded Target	Control
1954	4327	3468	1965	6912	5346
1955	4637	4227	1966	6305	5058
1956	2970	3156	1967	4756	3979
1957	3664	3430	1968	5248	4523
1958	5525	4989	1969	6017	5118
1959	5921	5135	1970	4600	4364
1960	7198	6444	1971	6149	5115
1961	4311	4356			
1962	4053	3730			
1963	4954	4586			
1964	4093	3823			

The change of the relative rainfalls for the seeded period is well apparent on the double-mass curve of Figure 3, and the annual variations show that the precipitation increase was maintained in the successive experimental years.

In order to evaluate the mean rainfall increase, Table 4 gives the rainfalls as percentages of the historical mean values for five periods of 7 years without seeding, and for the period of 7 years with seeding. Figure 4 shows the comparison of the Affected Area precipitations with that of the

Control Area for non-seeded and seeded periods. The historical correlation is .92 with a probability of .05. The double broken lines (Figure 4) limited a region of natural rainfall variation with .05 of probability. The point attributed to the seeding period (1965-1971) is clearly out of this region.

Table 4.

Rainfalls as Percentages of the Historical Mean Values in the Two Areas

Period	Target	Control
1954-1960	98,5	96,7
1955-1961	98,5	99,5
1956-1962	96,8	97,9
1957-1963	102,5	102,4
1958-1964	103,7	103,6
1965-1971	115,0	105,0

5. CONCLUSION

The continuous seeding for a seven year period from a ground generator near the French Atlantic Coast gives the response to this type of seeding in a full range of meteorological conditions: there is a rainfall increase up to 15% in an area of about 800 km^2 centered at 40 km downwind of the generator. This suggests a mean distribution of seeding material similar with the vertical distribution measured by GRANT, CHAPPELL and MIELKE (1971) during the ground seeding of orographic clouds upwind of a mountain barrier. In that way, sea breeze appears as convenient as up-valley wind for seeding convective clouds.

An ambiguous point remains: the generator was running very near the important kraft mill of Mimizan, and a possible inadvertent effect from the mill itself might be suspected. Therefore in the next period we plan to follow the rainfall level with either an interruption of the generator operation or its removal from the mill.

- - - - -

REFERENCES

Dessens, H., 1968: Experience de pluie provoquee par ensemencement ininterrompu a partir du sol. PROC. INT. CONF. ON CLOUD PHYS., University of Toronto, Canada, 719-723.

Dessens, J. and Pham Van Dinh, 1968: Le generateur a vortex. J. RECH. ATMOS., 3, 2e annee, 215-224.

Grant, L. O., C. F. Chappell and P. W. Mielke, Jr., 1971: The Climax Experiment for seeding cold orographic clouds. PROC. INT. CONF. ON WEATHER MODIF., Camberra, Australia, 78-84.

Lacaux, J. P., 1973: Recherche des effets sur la pluviometrie d'une emission continue de noyaux d'iodure d'argent. NOTE I.O.P.G. PUY DE DOME n°16, 23 p. (Unpublished Report).

Sauvageot, H. and G. Despaux, 1970: Dispositifs automatiques pour l'exploitation d'un reseau de generateurs de noyaus glacogenes. ASSOC. D'ETUDES DES MOYENS DE LUTTE CONTRE LES FLEAUX ATMOS., n°18, 64-77.

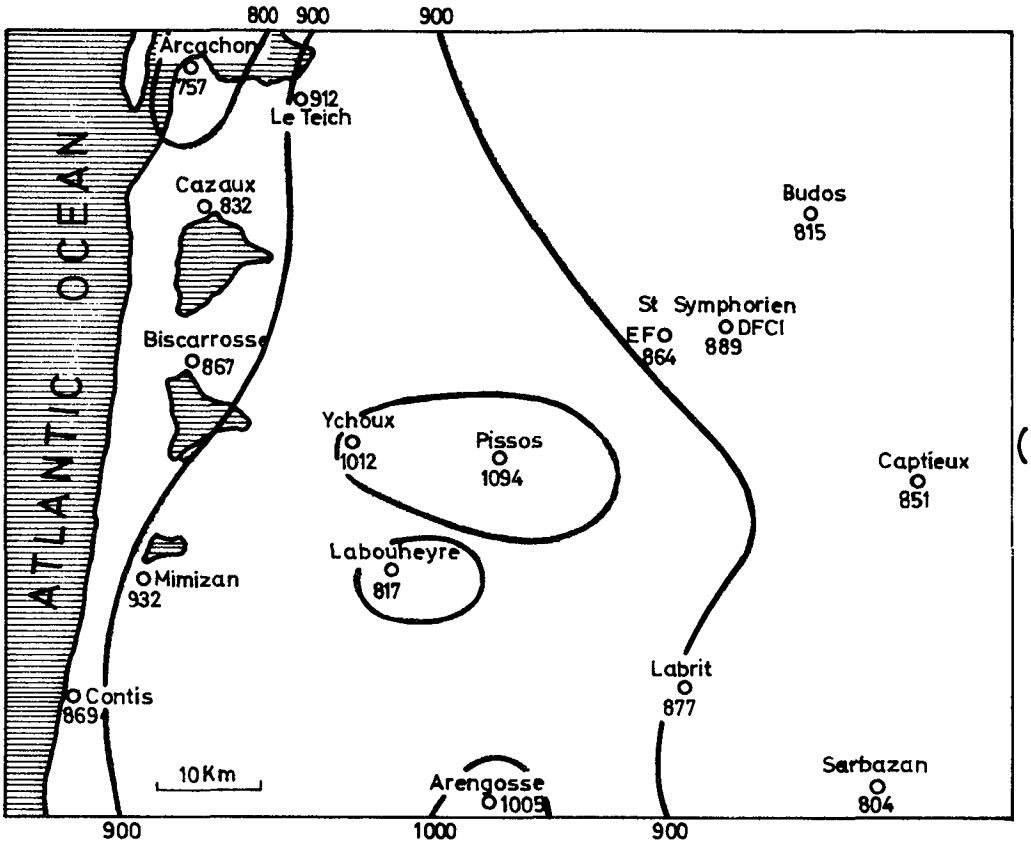
LEGEND FIGURES

Figure 1 - Mean annual rainfalls (in mm) for the historical period (1954-1964) and for the experimental period (1965-1971).

Figure 2 - The Affected Area (stations n° 8, 12, 14, 15, 16) and the Compound Control Area (stations n°1, 2, 4, 5, 9).

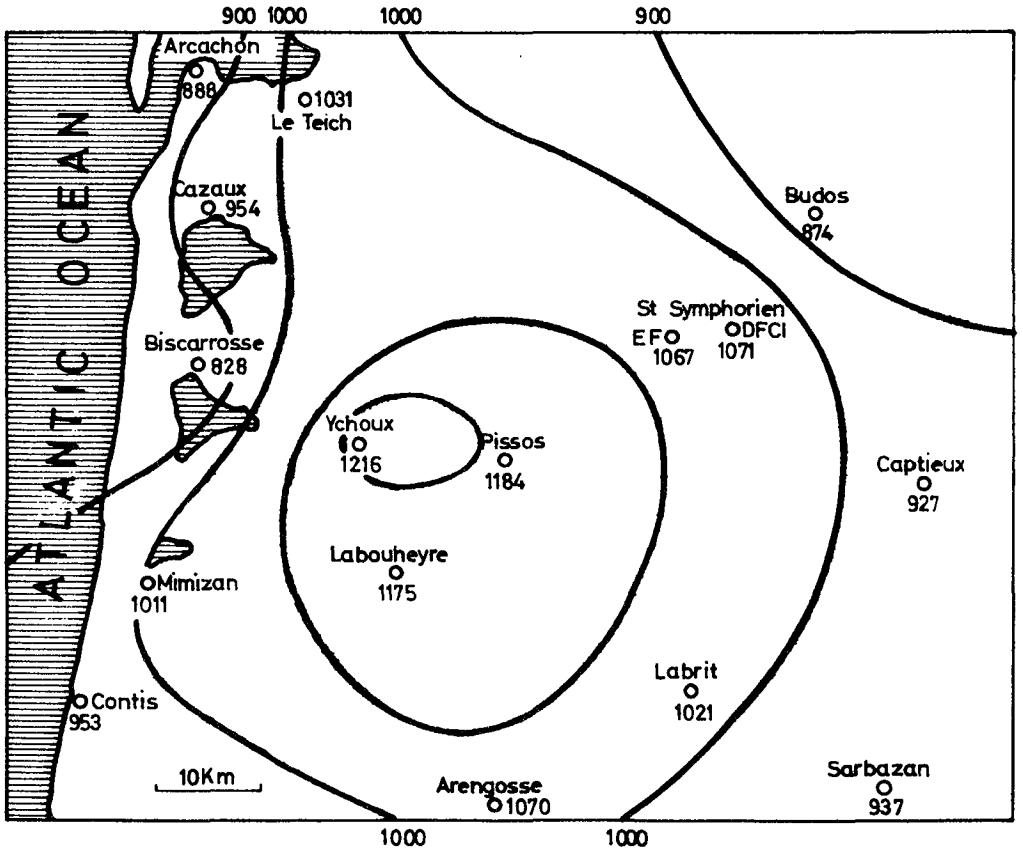
Figure 3 - Double-mass curve of the mean yearly rainfalls (in m.).

Figure 4 - Comparison of Target Area rainfall with Control Area rainfall for non-seeded and seeded years.



1954-1964

(NO SEEDING)



1965-1971

(SEEDING)

Figure 1.

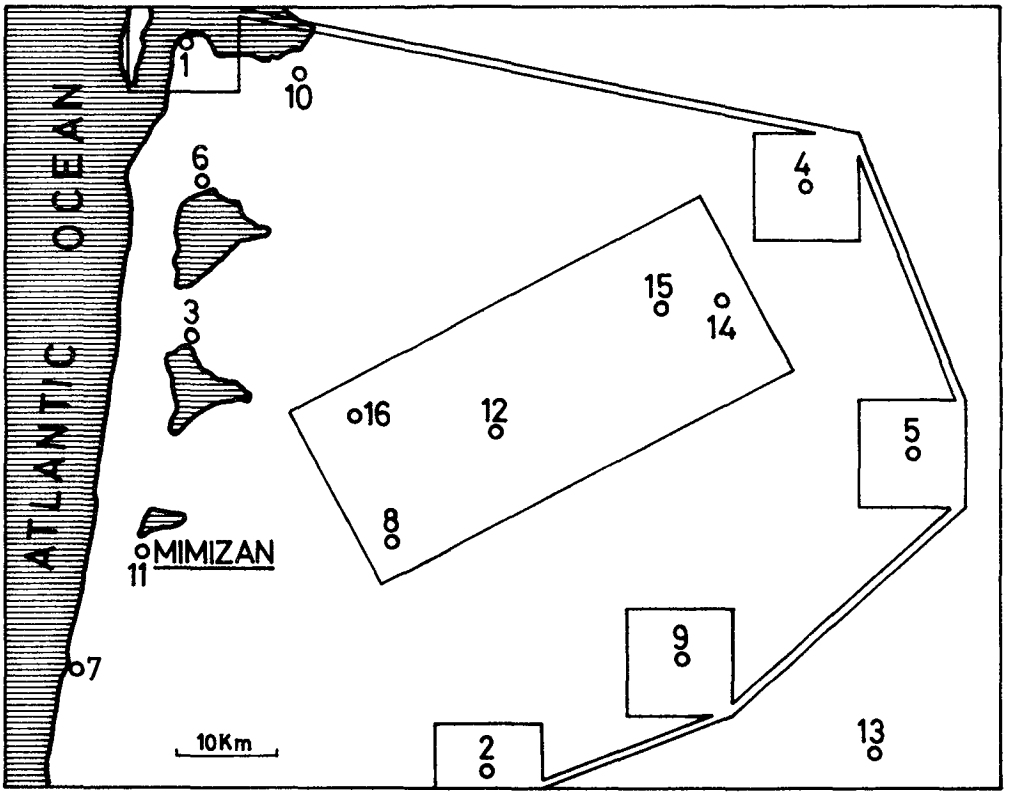


Figure 2.

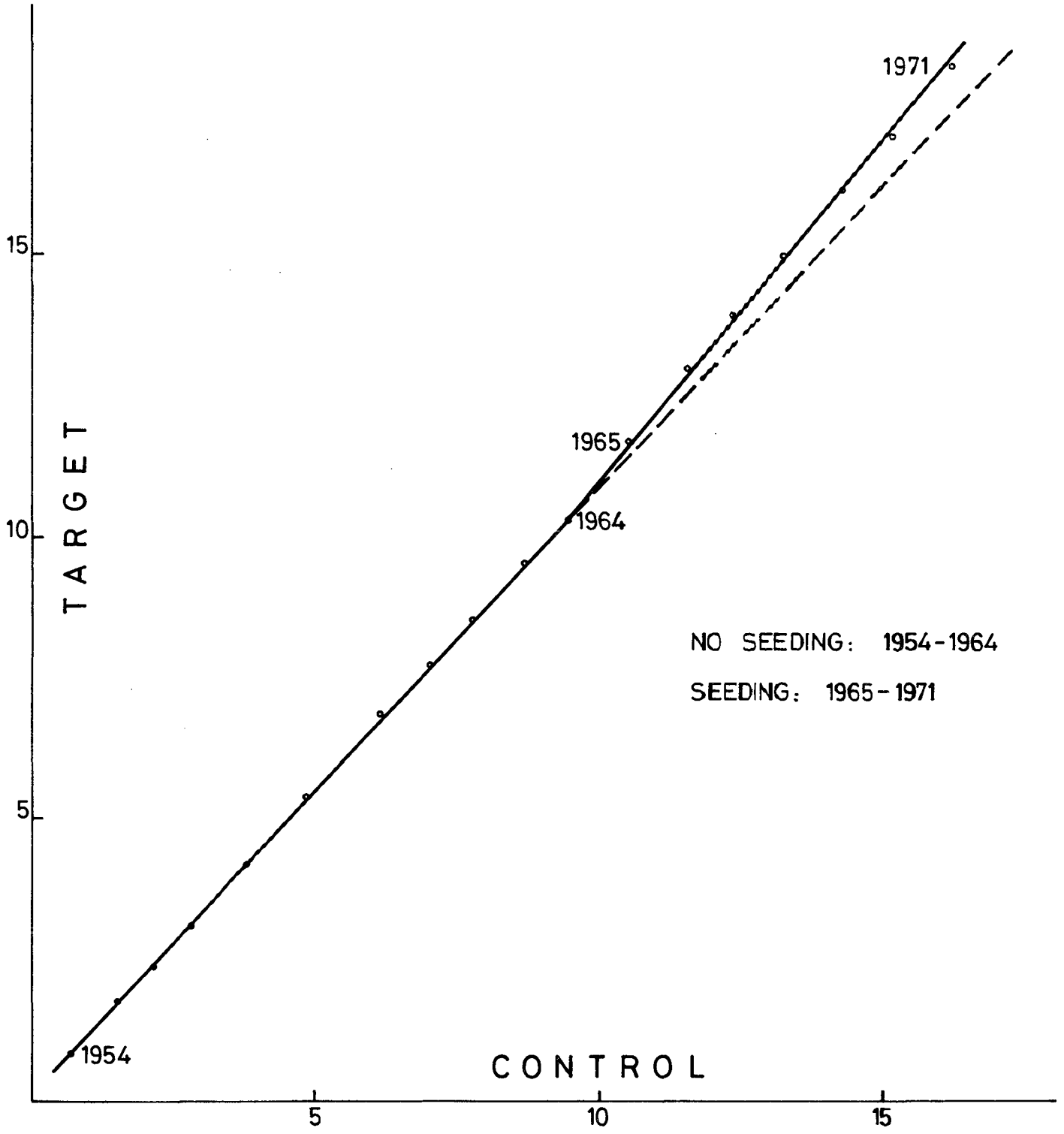

1971
1965
1964
1954
15
10
5
TARGET
NO SEEDING: 1954-1964
SEEDING: 1965-1971
CONTROL
5
10
15

Figure 3.

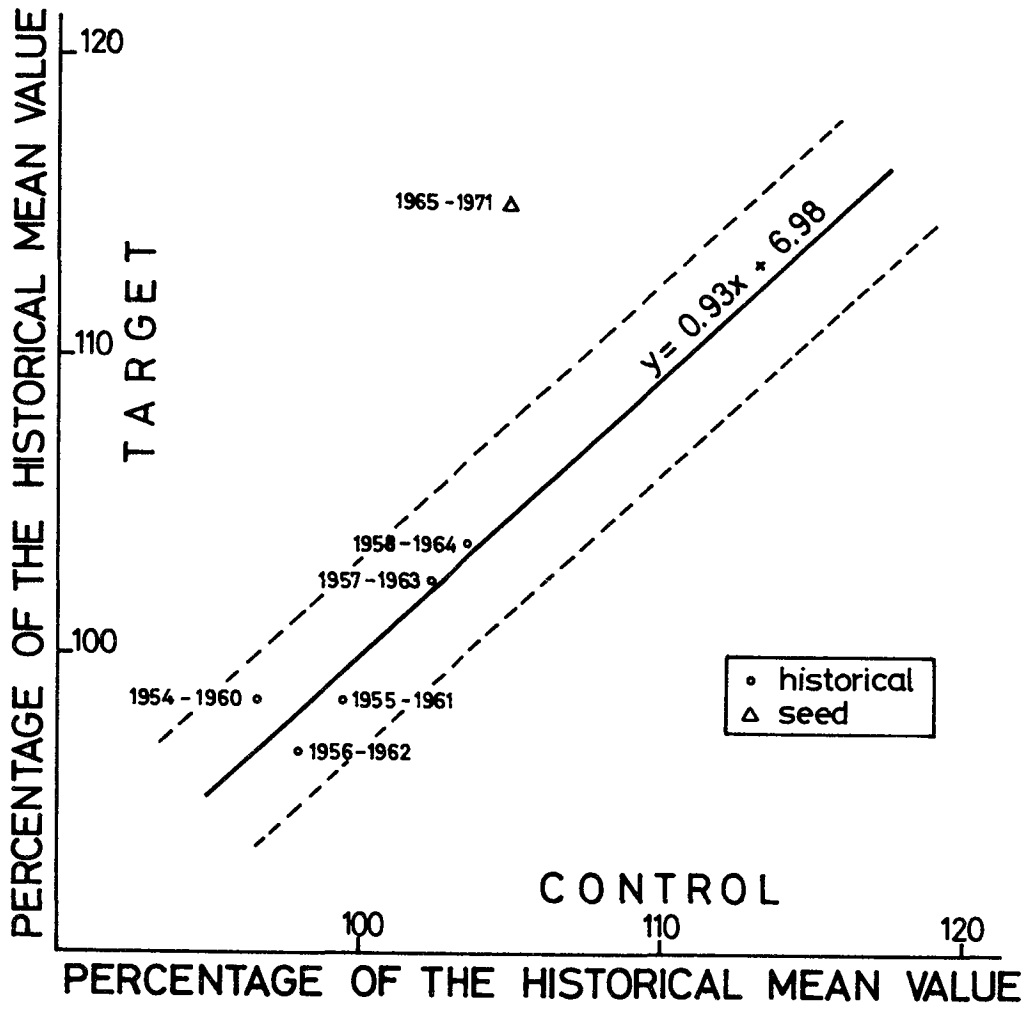

PERCENTAGE OF THE HISTORICAL MEAN VALUE
120
110
100
TARGET
1965 - 1971 Δ
y = 0.93x + 6.98
1958 - 1964
1957 - 1963
1954 - 1960
1955 - 1961
1956 - 1962
historical
seed
CONTROL
100
110
120
PERCENTAGE OF THE HISTORICAL MEAN VALUE

Figure 4.

FOG CLEARING WITH HELICOPTER DOWNWASH*

David H. Dickson

and

Walter S. Nordquist, Jr.

Atmospheric Sciences Laboratory
White Sands Missile Range, New Mexico

ABSTRACT

This paper summarizes the results of a literature search and a survey of helicopter pilots concerning the use of helicopter-induced downwash to effect temporary clearings in fog. While the technique has been successfully applied in a variety of situations, the available information indicates that the criteria for determining the probability of successful application of this method are yet to be completely established. In general larger helicopters, such as the CH-54, can be successfully used for clearing fogs of 500-600 foot depth; however, smaller helicopters, such as the UH-1, do not work well for fogs of depths over approximately 200 feet.

INTRODUCTION

Many years of research have been devoted to searching for methods of improving visibility within fogs. A relatively new method which appears to have merit, particularly for achieving temporary clearing over a small area, is that associated with the downwash created by a helicopter.

This paper contains a brief historical background on the use of the downwash technique for fog clearing, the results of application of the technique, tabularized accounts of the successes and failures by various categories of helicopter type and fog characteristics[a], and a few concluding remarks on what can be inferred from the information available.

BACKGROUND

Based on a 1961 experiment where water drops were dispersed from a helicopter (1) it was suggested that the downwash from the helicopter rather than

*This paper is an abbreviation of the material presented in Technical Report ECOM-5465 (15).

[a]Because of the variety of descriptors used for designating fog types, the descriptors used in this paper are those used in the information sources. The designations of shallow and deep refer to the vertical extent of the fog while thin and dense are used to designate the visual density of the fog (the less the horizontal visibility, the denser the fog).

the water drops caused the fog clearing (2), (3). The direct investigation of helicopter downwash as a fog clearing technique has a relatively short history. The first reported effort was that performed by the Cold Regions Research and Engineering Laboratories (CRREL) of the US Army above a thin-warm-advection fog along the wharf at Thule, Greenland in 1964 (4). In 1968 the US Air Force's Cambridge Research Laboratories (AFCRL) applied the technique to create "holes" in stratus clouds near Eglin Air Force Base, Florida (5), (6) and in ground and steam fogs at Smith Mountain Lake, Virginia (6). In 1969 the Atmospheric Sciences Laboratory (ASL) of the US Army joined with CRREL and AFCRL to conduct an extended series of tests applying the technique to radiation fogs near Lewisburg, West Virginia (7), (8), (9), while the US Army's Concept Team in Viet Nam (ACT IV) conducted a limited number of experiments on stratus cloud decks (10).

Since 1969 there have been helicopter downwash experiments on deep coastal advection fogs at Arcata, California in a joint ASL-Naval Weapons Center (NWC) effort in 1970 (11), on thin radiation fogs at Fort Rucker, Alabama by ASL (12), on ice fog at Fairbanks, Alaska by CRREL (13) in 1971, and on fog in the Panama Canal Zone by ASL and NWC in 1972 (reportage presently incomplete).

Additionally a survey of helicopter pilots on their experiences with the technique was conducted in 1971 (14), the responses are documented in (15) and summarized in (16). A report was subsequently made on the use of the technique for rescue purposes in Viet Nam (17).

RESULTS OF DOWNWASH MODIFICATION ATTEMPTS

A. General

Temporary clearings in a fog can be accomplished for a variety of fog conditions and of helicopter types. One important consideration in evaluating the status of the technique concerns what those who have observed the application of the technique have to say about it. This consideration provides a context for the interpretation of the tabulated data.

Thus, the first portion of this section contains a chronological ordering of quotes and comments about the technique as observed in the field. The statements indicate various anticipated results. The second portion summarizes the results in tabular form for the number of successes for depth categories by helicopter weight.

The tabular presentations have been prepared in "number of occurrences" form rather than in statistical form. This manner of presentation was chosen because of the limited number of experiments in each category and a lack of information on how many times the technique may have been tried, for fog modification or for other purposes, without success.

B. Quotes and Comments on the Technique

1964 - Following experiments using an H-34 helicopter Hicks (4) concluded: "...certain types of shallow fogs can be dispersed...by helicopters flying at

near-hovering air speeds at altitudes a few feet above the tope of the fog."

1968 - Following experiments using an HH-53 helicopter Plank and Spatola (5) stated: "...a large helicopter...should be able to create a swath of clearing, some 200-500 feet wide, along an airport runway 10,000 feet long, through ground fog 200 feet thick, in less than 10 minutes."

1968 - Following experiments using a CH-3E helicopter Plank (6) declared: "...helicopters can create operationally-useful clearing in particular types of ground fog of shallow depth and relatively-small liquid water content. A helicopter of the CH-3E type...should be able to accomplish effective clearing of such fogs in depths of 300 feet or so. Partial clearing, or visibility enhancement, might be achieved with fog layers as deep as 500 feet."

1969 - Following experiments using CH-46, CH-47 and CH-54 helicopters Plank, Spatola, and Hicks (7) concluded: "...created cleared zones ranging from 500 to 3000 foot size and produced appreciable visibility enhancement over zones even larger. Six helicopter landings were accomplished at the airport...through fog layers 200-400 feet thick."

(8)"...cleared zones large enough to permit helicopter landings can be created by single helicopters (of the types used in the Lewisburg program) in most naturally-occurring fog situations in which fog depths are less than about 300 feet. If multiple helicopters are employed...this will (a) increase the size of the cleared landing area in fog of 300 foot depth or (b) permit the creation of useable-size landing zones in fog of 400 foot depth, or possibly even fog of 500 to 600 foot depth..."

(9)"...the capability (to accomplish areal clearing) is nearly an order of magnitude greater for fog of 200 foot depth than for a fog of 500 foot depth."

1969 - Following experiments using CH-47 and CH-54 helicopters Christensen (10) stated: "...CH-47 and CH-54 helicopters were successfully used to dissipate fog and stratus clouds on four occasions."

1970 - Following experiments using a CH-54 helicopter (11) it appeared that short period clearing over limited areal extent could be accomplished for fogs as deep as 800 feet thick if the helicopter was flown in a tight circle immediately above the top of the fog. No noticeable clearings were noted for fog depths greater than 800 feet.

1971 - Following experiments usingCH-47 and CH-54 helicopters (12) it appeared that fog clearing could be accomplished with hover altitudes of 500 feet above ground or less.

1971 - Following experiments using a CH-47 helicopter Hicks and Kumai (13) concluded: "...clearings in ice fog large enough to allow VFR operations can be made under certain limited meteorological conditions..."

1971 - The comments received from helicopter pilots (15) responding to a survey (14) ranged from: "Decisively cleared area of operations" to "I don't believe that it is possible..."

C. Tabulated Data

Table 1 has been adapted from the published form of a lesson plan prepared by ASL for the Army Aviation School (18). This provides an overview of probabilities of success of the technique.

Data in Table 11 is extracted from the documented experiments and reported experiences totaling 117 individual cases, over half of which used the heavier helicopters (CH-47, CH-54, and HH-53). Table 11 presents cloud depth, the helicopter type, and success (YES = a clearing was observed, NO = a clearing was not observed) for each of the cases.

It is difficult to draw specific conclusions from Table 11; yet, interpretation of Table 11 in the light of the comments at the beginning of this section suggests that Table 1 may be fairly realistic. There does not seem to be any particular pattern to the exceptions within the presented categories in this paper.

TABLE 1

FOG DEPTH CLEARING BY HELICOPTER WEIGHT

Fog Thickness (FT)	Heavy	Medium	Light
100	Yes	Yes	Yes
300	Yes	Sometimes	Sometimes
500	Most of the time	No	No
700	Sometimes	No	No
1000	Occasionally	No	No

TABLE 2

SUCCESS OF HELICOPTER DOWNWASH FOG MODIFICATION
ATTEMPTS BY HELICOPTER TYPE

Helicopter	Success by Fog Depth (FT) (Yes/No)						Success Totals	
(Military Designation)	<100	100-249	250-499	500-999	<999	UNK	Yes	No
LIGHT								
OH-6A	--					2/1	2	1
UH-1	2/0	4/0	1/0			3/2	10	2
AH-1G	2/0						2	0
MEDIUM								
H-34			4/0				4	0
CH-34	--	1/0				1/1	2	1
CH-3E	1/0	1/0	10/0				12	0
HEAVY								
CH-46	1/0		8/0	1/0			10	0
CH-47	--	3/1	18/0	6/0		5/4	32	5
HH-53	--				3/1	1/0	4	1
CH-54	--	3/0	8/0	4/1	1/3	3/6	19	10
	6/0	12/1	49/0	11/1	4/4	15/14	97	20

CONCLUDING REMARKS

Helicopter downwash can be beneficial in attaining temperory clearing in fog with depths up to as much as 1,000 feet. The degree of success appears, however, to be small for such extreme thicknesses. Some assurance of success is available for the heavier helicopters (CH-47, CH-54 and HH-53) for fogs of depths less than about 500 to 600 feet and for the lighter helicopters (UH-1, OH-6A) for fogs less than approximately 200 feet deep. Information is not as yet available to determine the probability of success of fog clearing by helicopter downwash.

- - - - - - -

LITERATURE CITED

1. Magono, C., Katsuhire, T., T. Nakmura, and T. Kimura, 1963, "An Experiment on Fog Dissipation by Use of Downward Air Current Caused by the Fall of Water Drops," Journal of Applied Meteorology, 2 (4), 484-493.

2. Plank, V. G., 1964, "Comments on 'An Experiment on Fog Dispersion by the Use of Doward Air Current by the Fall of Water Drops', "Journal of Applied Meteorology, 3 (2), 213-214.

3. Magono, C., K. Katsuhire, T. Nakmura, and T. Kimura, 1964, "Reply," Journal of Applied Meteorology, 3 (2), 214.

4. Hicks, J. R., 1965 "Experiments on the Dissipation of Warm Fog by Helicopter-Induced Air Exchange Over Thule AB, Greenland," Special Report 87, U.S. Army Materiel Command, Cold Regions Research and Engineering Laboratories, Hanover, New Hampshire, 7 pp. (AD 474070)

5. Planks, V. G., and A. A. Spatola, 1969, "Cloud Modification by Helicopter Wakes," Journal of Applied Meteorology, 8, 566-578.

6. Plank, V. G., 1969, "Clearing Ground Fog with Helicopters," Weatherwise, 22, 91-98.

7. Plank, V. G., A. A. Spatola, and J. R. Hicks, 1970, "Fog Modification by Use of Helicopters," Preprints from the Second National Conference on Weather Modification, Santa Barbara, California, April 6-9, 1970 (American Meteorological Society).

8. Plank, V. G., A. A. Spatola, and J. R. Hicks, 1970, "Fog Modification by Use of Helicopters," U.S. Air Force, Cambridge Research Laboratories, Environmental Research Papers No. 335, and ECOM-5339, Atmospheric Sciences Laboratory, U.S. Army Electronics Command, White Sands Missile Range, New Mexico, 154 pp.

9. Plank, V. G., A. A. Spatola, and J. R. Hicks, 1971, "Summary Results of the Lewisburg Fog Clearing Program," Journal of Applied Meteorology, 10, 763-779.

10. Christensen, G. F., 1970, "Use of Helicopters to Dissipate Fog," Letter Report, ACTIV Project No. ACA-1/701, U.S. Army Viet Nam, 4 pp, (AD 866650).

11. Nordquist, W. S., ed., 1972, "Data from a Fog Dispersal Experiment Using Helicopter Downwash," ECOM-5456, Atmospheric Sciences Laboratory, U.S. Army Electronics Command, White Sands Missile Range, New Mexico.

12. Dickson, D. H., 1972, "FOGWASH 1: An Experiment using Helicopter Downwash," ECOM-5431, Atmosphric Sciences Laboratory, U.S. Army Electronics Command, White Sands Missile Range, New Mexico.

13. Hicks, J. R., and M. Kumai, 1971, "Ice Fog Modification by Use of Helicopters," Special Report 162, U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratories, Hanover, New Hampshire, 11 pp. (AD 731215).

14. Dickson, D. H., ed., 1971, "Fog Dissipitation Questionnaire, " Aviation Digest of the U.S. Army, 17, 6

15. Nordquist, W. S., and D. H. Dickson, 1972, "Helicopter Downwash Applied to Fog Clearing: A Status Summary," ECOM-5456, Atmospheric Sciences Laboratory, U.S. Army Electronics Command, White Sands Missile Range, New Mexico, 13 pp.

16. Dickson, D. H., ed., 1972, "Fog Dissipitation Questionnaire Results," Aviation Digest of the U. S. Army, 18, 24-25.

17. Anonymous, 1969, "Helicopter Technique for Clearing Warm Fog and Clouds", OAR Research Review, 8, 10.

18. Dickson, D. H., and J. R. Oden, 1972, "Fog Dissipation Techniques for Emergency Use," ECOM-5420, Atmospheric Sciences Laboratory, U. S. Army Electronics Command, White Sands Missile Range, New Mexico, 35 pp.

- - - - - - -

RESULTS OF THE BOWMAN-SLOPE HAIL SUPPRESSION PROGRAM

A. F. Butchbaker

North Dakota State University
Fargo, North Dakota

Faced with high crop-hail insurance rates and large crop losses due to hail, farmers near the Bowman area formed the Bowman-Slope Hail Suppression Association in 1961. The average loss cost in Bowman County exceeds 13 per cent, compared with a state average of approximately five per cent. Crop-hail insurance rates range from 14 to 22 per cent of the insured liability for this area (1).

This southwestern corner of North Dakota lies on the eastern edge of a north-south hail band east of the Rocky Mountains extending from northeastern Montana to southeastern New Mexico in the United States.

No attempts to determine the effectiveness of the Bowman-Slope cloud seeding program or the hailfall climatology of the area were made until 1965, when a preliminary investigation was undertaken (2). More detailed reports have been prepared for each of the years since 1965 (3, 4, 5, 6,).

The objectives of the research were: to determine the radar and hailfall climatology of seeded and unseeded storms near the vicinity of a hail suppression project; to determine whether there were significant reductions in hail intensity due to the seeding program; and to determine whether precipitation was altered in the vicinity of the hail suppression program.

THEORY OF HAIL SUPPRESSION

There is a variety of storm types by which Nature creates hail. Some are small-scale thunderstorms of short duration; others are quite massive and last several hours. Some of the storms are associated with frontal

---

This project was supported by North Dakota Agricultural Experiment Station Project H-4-18, and National Science Foundation Grant NSF GP5485, and NSF GA857.

Dr. Butchbaker was formerly associate professor, Agricultural Engineering Department, North Dakota State University, Fargo, North Dakota, now on the staff of the Agricultural Engineering Dept. at Oklahoma State University, Stillwater, Oklahoma.

weather systems and squall lines; others may be isolated cells arising from convective heating of air near the surface of the ground. However, all of them have at least one common characteristic: updraft regions where warm moist air is drawn into the storm. The air cools as it rises and as the rising water vapor condenses it releases latent heat, creating a further unstable condition.

Hailstones are believed to be formed in that part of the storm which possesses a high concentration of supercooled water (water below 32°F that has not frozen). Large hailstones may remain in this environment or cycle between this wet environment and a cooler drier environment until they reach such a size that they can fall through the updrafts and reach the ground. The development of hailstones in a storm are not completely understood.

Most hail suppression programs are based upon the theory of seeding potential hail-producing storms with silver iodide to turn all of the supercooled cloud droplets into ice crystals. By glaciating (turning to ice crystals) the supercooled water in the air parcels through which the hail embryo passes, the hailstone's growth will be inhibited. It is generally assumed that complete glaciation will completely stop the growth.

Another theory suggests that if the number of hail embryos can be sufficiently increased by seeding, there will not be enough supercooled water for any of them to grow large. Thus, many more hailstones may be formed but they will be smaller and perhaps slushy if they reach the ground before melting.

OPERATION OF HAIL SUPPRESSION PROGRAM

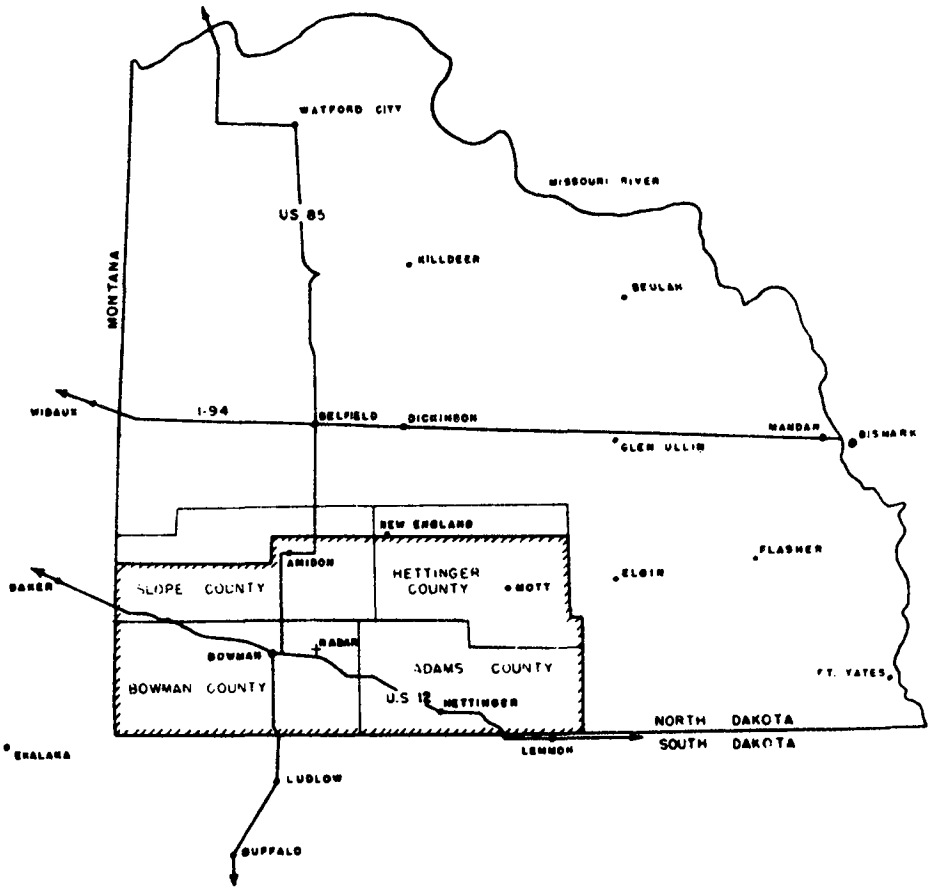
Bowman-Slope Hail Suppression Association

After some particularly severe crop hail losses in 1960 (and also for a period of years between 1954 and 1960), Wilbur Brewer, William Fisher, and their farm neighbors organized the Bowman-Slope Hail Suppression Association. The association collected money on a voluntary basis on the seeded acerage. The original area covered a strip 18 miles wide and 30 miles long. The seeded area expanded from covering portions of Bowman and Slope Counties in 1961 to a four-county area of Bowman, Slope, Adams, and Hettinger Counties in 1968 and 1969, an area of approximately 3,200 square miles. Figure 1 shows the seeded area during 1968.

During the early years of the project, two farmer-pilots, Brewer and Fisher, were contracted by the association to seed the thunderstorms with Lohse wing-tip silver iodide generators. For the first two years, the clouds were aircraft-seeded only during daylight hours. However, there were heavy losses at night, so operations were changed to a 24-hour day, seven-days a week alert, between June 1 and September 1. In addition to the aircraft, 20 Sky-Fire ground generators were located throughout the target area between 1963 and 1967. Between 1961 and 1965, the pilots relied upon their visual observations of storms and telephone reports of incoming hail-

Figure 1

Location of radar site, major towns and boundaries in the study area



storms from people in the western part of the area and also on radio weather reports. Upon observing the likely hail producing clouds, they would fly out to meet the cloud on the edge of the target area, where they would locate the strongest updraft for dispensing the silver iodide into the cloud.

Operation Since 1966

A 3-cm radar system was leased by the association during 1966 to detect thunderstorm cells as they approached the target area. The radar was equipped with planned position indicators (PPI) which permitted the radar operator to observe storm cells and to measure the storm reflectivity. Also, thunderstorm tops were measured by noting the echo range and the antenna tilt angle where a thunderstorm top disappeared on the scope.

Generally, an operational day began with a weather briefing via telephone among personnel of the Institute of Atmospheric Science, South Dakota School of Mines and Technology, Rapid City, and the radar operator at Bowman, North Dakota. On days when thunderstorms were probable, the

radar operator maintained close vigilance on latest developments in eastern Montana and western North and South Dakota. Upon noting the minimum gain reading of radar reflectivity, the radar operator would notify the pilots. The pilots would then try to intercept these storms near the target area on either daytime or nighttime flights and seed silver iodide by Lohse-type wingtip generators or pyrotechnic flares at approximately a -4°C level near the cloud base. The radar operator was in radio communication with the pilots during the seeding flights and could direct the pilots to various cells that looked like potential hailers. Table I presents a summary of the seeding activities over a period of three years. A large increase in seeding materials per storm for 1967 and 1968 was due primarily to the increased use of pyrotechnic flares which dispensed the silver iodide from electricity ignited airborne flares.

TABLE 1

Seeding Information

	1966	1967	1968
Number of seeding planes	2	3	4
Seeded area (sq. miles)	1980	2300	3200
Number of seeded storms	24	19	31
Seeding material used (gms. silver iodide)	29,960*	54,780**	95,710**
Seeding material per seeded storm	1,250	2,880	3,087

*4% silver iodide-in-acetone burned by wingtip generators
**airborne pyrotechnic devices and wingtip generators

EXPERIMENTAL EQUIPMENT AND PROCEDURES

Data acquisition devices for the research program included radar system, aluminum-foil-overstyrofoam hail indicators, rain gages, questionnaires, pilot flight logs, and facsimile weather charts.

Radar

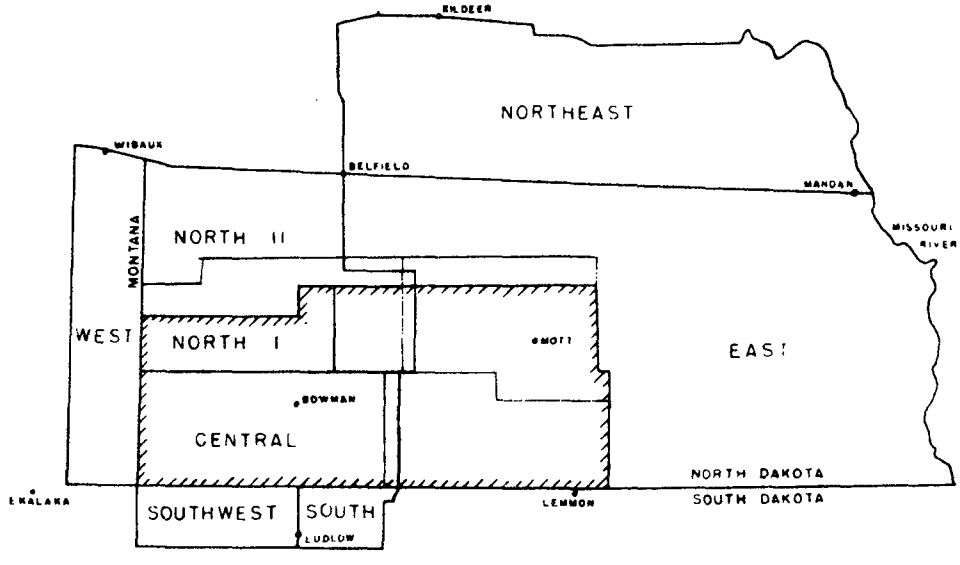
The radar operator took overlays on the radar scope of the echoes and recorded the minimum gain setting before the echo disappeared, the angles to the radar echo cloud top height, and the range of the echo from the radar site. Radar reflectivities and cloud top heights were computed later. Overlays, taken approximately every 15 minutes, permitted the storm paths to be determined.

Ground Indicators.

A network of hail indicators and rain gages were located in the target area and in the control areas as shown in Figure 2. The indicators were located at approximately three-mile intervals on easily accessable roads. Dented aluminum foils on the hail indicators were replaced after each hailstorm and were analyzed to obtain hailfall energy values in foot-pounds per square foot, using a calibration method developed by Schleusener and Jennings (7). The rain gages were constructed of quart oil cans and mounted about one foot above the ground. To prevent evaporation between readings light lubricating oil was placed in the rain gages.

Figure 2

Location of various study areas for hail indicator and raingage sites



Other Data Sources:

Questionnaires of the hailfall were distributed to approximately three farmers in each township of the seeded area. The questionnaires were used to determine the onset and duration of the hailfall, nature of the hailstorm, and wind velocity in a particular location. The pilots completed flight logs after each seeding flight, indicating seeding flight paths, time of generator operation, and time pyrotechnic flares were used. Weather Bureau facsimile charts were used to determine the location of major synoptic conditions at the time of occurrence of the hailstorm.

RESULTS

Climatology of Hailstorms

Occurrences of Hailstorms. Table 2 presents a summary of the storm occurrences for the three years. The 1968 year had the highest number of thunderstorm days and days with cloud seeding. This was partially due to an increase in size of the seeded area. The 1966 year was also one with considerable hail activity in a study area, which was smaller than for 1967 or 1968.

TABLE 2

Summary of Storm Occurrences

	1966	1967	1968
Thunderstorm days	32	20	38
Hailfall days in target or control areas	19	15	19
Days with heavy hail	8	5	5
Days with seeding	20	16	27
Number of storm systems seeded	24	19	31
Seeding days with no hail	7	7	8

Radar Climatology. Table 3 presents a summary of the radar climatology data for cloud top height and maximum radar reflectivity. The mean cloudtop height was significantly higher for the hailers than for the non-hailers for each individual year. The mean of the radar reflectivities for hailers was greater than the mean of the non-hailers for each of the three years. There was also considerable variation between years, as evidenced by the statistically significant differences between years for nearly all categories.

Hailfall Climatology. Table 4 presents a summary of the hailfall climatology for the three years. Between 50 and 80 per cent of the indicators recording hailfall had less than 10 foot/pounds per square foot of hailfall energy. This represents very little damage to a small grain crop. Between one-sixth and one-third of the indicators recorded 10 to 40 ft-lbs/sq ft., representing some damage to crops. Only 3 to 6 per cent of the indicators received over 40 ft-lbs/sq.ft. of hail energy, representing serious hail damage to small grains.

TABLE 3

Summary of Radar Climatology Data

	1966	1967	1968	Probability level of which diff. are significant between years
Mean Cloud Top Height (ft-MSL)				
Non-hailers	32,600d	34,600	30,400	2.5
Hailers	41,200	36,700	41,100	Insig.
Mean Radar Reflectivities (mm^6/m^3)				
Non-hailers	$1.38x10^7$c	$0.95x10^7$	$0.96x10^7$	5.0
Hailers	$5.27x10^7$	$1.30x10^7$	$1.47x10^7$	0.5
Before Seeding	$8.30x10^7$a	$1.54x10^7$c	$9.8x10^7$d	0.5
After	$3.97x10^7$	$0.87x10^7$	$1.0x10^7$	0.5

a Significant difference at p = .05
b Significant difference at p = .025
c Significant difference at p = .01
d Significant difference at p = .005

TABLE 4

Summary of Hailfall Climatology Data

	1966	1967	1968
Percent of indicators with hail energy in ft-lb/ft^2 between			
0-10	83	80	61
10-40	14	17	33
40+	3	3	6
Time periods having higher frequency of occurrences of storms	1000-1200 1400-1600 1800-2000MST	1400-1600 MST	1400-1600 MDT
Percent of storms having hail-fall duration in minutes between			
0-5	47	65	50
5-20	51	23	30
20+	2	12	20

The time period having the highest occurrence of hailstorms was from 1400 to 1600 MST (2 to 4 PM). This suggests that most storms developed in the afternoon from thermal effects.

The hailfall duration at a point location, for about 50 per cent of the storms, lasted five minutes. Less than 20 per cent of the storms had hailfall lasting over 20 minutes. Table 5 presents a summary of the hailfall energy data for each year in various study areas. The 1966 year had the highest hailfall intensities, and 1967 the lowest. There were statisti-

TABLE 5

Summary of Hailfall Energy Data

	1966	1967	1968	Probability level of which diff. are significant between years
Mean seasonal hail energy ($ft\text{-}lb/ft^2$)				
Target area	9.22	1.37	2.14	0.5
Control areas				
North I	1.97	0.44a	0.76b	5
South	14.13b	2.07b	4.92c	0.5
West	13.66b	0.42b	4.63a	0.5
Southwest	-	3.636	8.19d	Insig.
Northwest	-	1.39	2.49	

a Significant difference at p = .10
b Significant difference at p = .05
c Significant difference at p = .01
d Significant difference at p = .005

cally significant differences between the years for most of the study areas indicating considerable variations from one year to the next.

Precipitation Climatology. Table 6 presents a summary of the precipitation data for the three years. All indicator sites received precipitation during each summer, but not all sites had hail damage. The 1966 year had the highest precipitation of the three years, and also the highest mean hailfall energy. The 1967 year had the lowest precipitation and also the lowest hailfall energy.

TABLE 6

Summary of Precipitation Data

	1966	1967	1968	Probability level of which diff. are significant between years
Mean seasonal precipitation (inches)				
Target area	8.95	4.13	5.76	0.5
Control areas				
South	7.33b	4.22	5.20	0.5
West	9.99a	3.59	5.05	0.5
North I	9.41	3.13b	4.83a	0.5
Southwest	-	3.56	6.71c	0.5

a Significant difference at p = .05
b Significant difference at p - .01
c Significant difference at p = .005

Evaluation of Cloud Seeding Effects

Researchers used three methods of analyses trying to detect changes which the cloud seeding for hail suppression might have produced. These included a review of individual storms, a comparison of radar reflectivities before and after seeding, and an analysis of total seasonal hail energies received in the seeded area versus unseeded areas. Additional comparisons were made for precipitation in the target and control areas.

Individual storms. To test whether cloud seeding for hail suppression causes changes in the hailfall intensity, a check was made for cases where hail intensity increased or decreased after seeding. If seeding had no effect, the chance for an intensity increase would equal an intensity decrease.

The hail energy distribution, pilot's flight paths, and successive positions of the severe portion of each seeded thunderstorm were examined, as well as the changes in thunderstorm tops and radar reflectivities. From these considerations, a subjective decision was made as to whether seeding may have caused an increase or decrease in hail intensity at the ground. In cases where hailfall intensity data were lacking, a change in hail intensity did not occur or the storm developed in the target area, no decisions on seeding effects were made. Table 7 presents a summary of the effects of seeding an individual storm system.

TABLE 7

Summary of Effects of Seeding on Individual Storm Systems

	1966	1967	1968
Number of seeded cases	24	19	31
Number of seeding days	20	16	27
Number of hail cases	17	9	19
Seeded days with no hail	7	7	8
Days with insufficient data for decision			3
Seeded cases for comparison	17	9	16
Cases with decreasing reflectivity and hail intensity after seeding	8	6	7
No decision cases with little or erratic changes in hailfall and reflectivity after seeding	8	3	9
Cases with increasing reflectivity and hailfall after seeding	1	0	0
Probability of obtaining combination of numbers of increases and number of decreases	.04	.0156	.0078

The results for the three years indicated that from one-fourth to nearly one-half of the seeded cases had no hailfall. No one knows whether this resulted from cloud seeding for hail suppression or whether hail would not have naturally fallen from these storms. Roughly one-half of the cases where hailfall occurred had definitive changes. The remaining one-half of the hailfall cases had little change in hailfall intensity or radar reflectivity after seeding or had very erratic changes with pulsating effects. No decisions as to the effect of seeding was made for these cases.

Of the cases where well defined changes in hailfall and radar reflectivity occurred, nearly all indicated a suppressive effect. Only one, during 1966, indicated an increase in hail intensity and radar reflectivity after seeding.

On the basis of these individual storm responses to seeding, it was found that:

1) Approximately one-third of the potential hailers have no hailfall after cloud seeding.

2) One-third of the storms continue to emit hail periodically after seeding or do not change appreciably.

3) One-third of the storms have decreasing hail intensity and radar reflectivity after seeding.

4) A very low probability exists for hailers to have increasing hail intensity and radar reflectivity after seeding.

The storms mentioned in the first conclusion may never have hailed naturally. However, based upon the maximum radar reflectivities, cloud top heights, and other features, these storms appeared to have the potential for hail. Therefore, preventitive cloud seeding for hail may have been accomplished for these cases. The evaluation of suppressive effects can only take place when hail has fallen.

Radar Reflectivity Changes. To test the hypothesis that seeding causes changes in maximum radar reflectivity of the individually seeded storms, a comparison of reflectivity observations taken before seeding and those after seeding can be made.

Table 3 presents the means of the radar reflectivity for before and after seeding for each of the three years. There were statistically significant differences between the before and after seeding cases for each of the years. There was also a significant difference between years, indicating considerable variation between years.

Comparison of Total Hail Energies. If cloud seeding effectively reduced the hail, the total seasonal hail energy received in the target area should be lower than comparable control areas. To test this hypothesis, the total June, July, and August hail energy at each indicator location was computed and the energy totals for each area statistically compared.

Table 5 presents a summary of the mean seasonal hailfall energy for each study area. The target area had significantly less hailfall energy than the south and southwest unseeded control areas. Except for the 1967 year, the target area also had significantly less hail energy than the west control areas. The North I area had significantly less hail energy for each of the three years than the target area. Many of the storms passing over the North I area had been seeded previously over the target area. There were significant differences between years for each study area, indicating considerable variation in hailfall energy from year-to-year.

In addition to hail energy comparisons, seasonal precipitation was compared between the target area and the control areas (Table 6). In general, there were little significant differences in precipitation betwen the target

area and the various control areas each year. However, significant differences between years existed for each study area.

The results of these comparisons indicate that hailfall energy is less in the target area than nearby unseeded control areas, particularly the south and southwest areas. The areas downwind from the target area either had no difference in hailfall energy or less hailfall energy than the target area. In general, little differences in seasonal precipitation were found between the target area and unseeded control areas or control areas contaminated from the seeding.

The results of this investigation suggest that hail is suppressed in a seeded area compared with nearby unseeded areas without significantly changing the precipitation in the seeded or unseeded areas. Also, a low probability exists for increases in hail intensity after seeding and a relatively high probability exists for either no hail or decreasing hail intensity after seeding potential hailers or storms already hailing.

SUMMARY OF RESULTS

The results of this investigation indicated: (1) a 30 to 60 per cent reduction in hail intensity in the target area compared with the south and west control areas,(2) significant differences in storm characteristics between before and after seeding and in seasonal hail energy between seeded and unseeded areas, (3) a low probability was found for increases in hail intensity after seeding, (4) one-third of the seeded storms did not hail, one-third had decreasing hail intensity after seeding, and one-third did not change appreciably in hail intensity after seeding, (5) the southwestern North Dakota area had thunderstorm days between on-fourth and one-third of the days between 1 June and 1 September with potential hailstorms on about three-fourths of these days, (6) the cloud top heights and maximum radar reflectivities were significantly higher for hailers than for non-hailers, and (7) hailstorms occurred most frequently between1400-1600 (2 to 4 P.M.) MST with most storms having a hailfall duration of less than five minutes and hailfall energy less than 10 ft-lb/sq.ft.

REFERENCES

1. North Dakota 1966 Crop-Hail Insurance Statistics. Crop-Hail Insurance Actuarial Association, Chicago, Illinois, 1967.

2. Flannagan, M.J., A. F. Butchbaker, et.al., Observations of Convective Storms in Connection with a Hail Suppression Project, Joint report by Institute of Atmospheric Science, S. Dak. School of Mines and Technology, Rapid City, South Dakota and Agricultural Engineering Dept., N. Dakota State University, Fargo, N. Dak., 1966.

3. Hagen, L.A., Climatology of Hailstorms and Evaluation of Cloud Seeding for Hail Suppression in Southwestern North Dakota, unpublished M.S. thesis, NDSU, Fargo, N. Dak., May 1967.

4. Butchbaker, A. F., Results of 1967 Hail Suppression Program in Southwestern North Dakota, Agricultural Engineering Dept. Report, North Dakota State University, Fargo, North Dakota 1969.

5. Butchbaker, A. F., Results of 1968 Hail Suppression Program in Southwestern North Dakota, Agricultural Engineering Department Report, North Dakota State University, Fargo, North Dakota 1969.

6. Butchbaker, A. F., Summary of the Results of a Hail Suppression Program in Southwestern North Dakota, Agricultural Engineering Department Report, North Dakota State University, Fargo, North Dakota, 1969.

7. Schleusener, R. A. and P. C. Jennings, "An Energy Method for Relative Estimates of Hail Energy," Bull. of Am. Meteor. Soc., 41: 372-376. July 1960.

- - - - - -

THE USE OF HIGHLY CHARGED HYGROSCOPIC DROPS FOR FOG DISPERSAL

John W. Carroz
Pierre St.-Amand
Donald R. Cruise

ABSTRACT

Hygroscopic solutions sprayed into a fog can be used to disperse the fog and to improve visibility. However, present techniques require such large amounts of material that cost and inconvenience make them unattractive for large scale routine use. This paper estimates the advantages to be gained from electrifying the drops of hygroscopic material.

The growth of an electrically neutral hygroscopic drop by diffusion of water vapor was calculated using Fukuta's equation. To this was added the growth by collision followed by coalescence with smaller uncharged droplets of the fog.

The growth by collision and coalescence for an electrically charged drop falling through a fog was calculated using Cochet's equations. Fukuta's equation was used to calculate the diffusional growth of a charged drop. The growth by diffusion was added to that by collision.

The uncharged drops of hygroscopic solution should grow from 40 to 88 microns in 200 meters of fall. Hygroscopic drops of 40 microns radius charged to the Rayleigh limit should grow to 112 microns, a gain of 22 times the initial volume.

These calculations were then used to estimate the fog clearing potential of electrically charged drops. It should be possible to increase the visibility in fog up to 20 times when treating advection type fogs with as little as 10 gallons per acre of agent. The visibility increase is less when a significant portion of the fog droplets is smaller than a few microns.

The feasibility of fog clearance can be improved if a method for charging the spray droplets to near the Rayleigh limit can be developed.

INTRODUCTION

A number of methods have been devised and used to clear fog. Fog occurring at temperatures below $0^{o}C$ and composed of liquid water droplets can be cleared easily, if less than 1,000 meters thick, by seeding with nuclei that induce freezing. Water droplet fogs occurring in air warmer than $0^{o}C$ are much more difficult to eradicate. The techniques envisioned and tried include: heating the air to evaporate the fog, mixing dry air from above the fog with the fog to cause it to evaporate, filtering the fog from the air, sweeping the fog particles away by dropping various materials into it, drying the fog out by spraying or distributing hygroscopic agents in it, etc. These techniques and many variations of them have been successful under special conditions, but expense or operational difficulty has precluded wide spread use of any of them.

The Earth and Planetary Sciences Division, Michelson Laboratory at China Lake, California, has conducted extensive fog dispersal tests with various hygroscopic agents. Because of ease of handling, cheapness, hygroscopicity and innocuous or beneficial ecological effects, we have used a solution of urea, ammonium nitrate and water in approximately equimolar proportions. Sensu strictu this is not a solution but is a melt; the melting point of eutectic, urea-ammonium nitrate is depressed by the addition of water. The material and the results of the field trials and laboratory tests are reported in Blomerth, et al., (1970), Clark, et al., (1971), Wright, et al., (1972).

DROP SIZE CALCULATIONS

Diffusional Growth

Fukuta's equation (Fukuta 1970) was used to calculate the hygroscopic growth. For a solution drop in air of saturation ratio, S, the growth rate is

$$\frac{dm}{dt} = 4\pi r_s' \,(S-A) \Big/ \left[\frac{AMLL'}{RT_\infty^2 K \delta_{3a}} + \frac{RT_\infty}{DMp_{\infty,sat}\delta_{3\beta}} \right] \tag{1}$$

where

$$A = \frac{n}{n + in'} \exp\left[\frac{2\sigma' V_L'}{r_s' RT\infty} \right] \tag{2}$$

where

m = mass of drop
t = time
r_s' = radius of solution drop
S = saturation ratio
A = combination of Kelvin and solute effects, defined by Fukuta
M = molecular weight of water
L = latent heat of condensation of water vapor
L' = latent heat of condensation of water vapor in solution
R = universal gas constant
$T\infty$ = ambient temperature
K = thermal conductivity of air
δ_{3a} = correction factor for temperature difference, defined by Fukuta
D = diffusion coefficient of water vapor in air
$p_{\infty,sat}$ = saturated water vapor pressure at ambient temperature,
$\delta_{3\beta}$ = correction factor for vapor density difference, defined by Fukuta
n = number of moles of solvent, that is, water
n' = number of moles of solute
i = van't Hoff factor for non-ideal solution
σ' = surface tension of solution drop
V_L' = molar volume of water in solution

This growth equation differs from previous equations (Maxwell, 1879; Rooth, 1957; and Langmuir, 1961) in that discrete vapor and temperature fields at the surface of growing drops are considered.

It is assumed, perhaps incorrectly, that an electrical charge will have no effect on the rate of growth of drops by diffusion of water vapor thereunto. The same equations are therefore used for water vapor accretion by both charged and uncharged drops.

Growth by Accretion, Uncharged Drops

The treatment here involves only vertical fall of the treatment drops through the fog. The uncharged drops are assumed to fall faster than the fog droplets and sweep them up by Smoluchowskian capture. No effects due to electrical charge or to diffusiophoresis are included.

The basic equation is

$$N = \pi \int_0^\infty \int_0^\infty (V_T - V_F)(r_s' + r)^2 E n_T n_F dr_s' dr \qquad (3)$$

where

- N = Number of collisions, equated to number of droplets collected per unit volume per second.
- π = Ratio of circumference to diameter of a circle.
- r = Radius of fog droplets.
- V_T = Gravitational fall velocity of treatment drops.
- V_F = Gravitational fall velocity of fog droplets.
- E = Smolochowskian capture coeffieient.
- n_T = Number of treatment drops per unit volume.
- n_F = Number of fog droplets per unit volume.

Assuming a monodispersed fog, in which the V_T is large compared to V_F, and a monodispersed treatment, this reduces to

$$N = \pi V_T (r_s' + r)^2 E n_T n_F \qquad (4)$$

Because $E = f(V_T, V_F, r_s', r)$, calcuation of capture must be done by a stepwise integration.

The volume accreted by the treatment and added to the treatment drops is

$$V_c = \frac{4}{3}\pi r^3 N \qquad (5)$$

The resultant volume, V_R of the treatment drops after collection is

$$V_R = V_C + V_T \tag{6}$$

The coalescence factor in these calculations is assumed to be unity.

Growth by Accretion, Charged Drops

Because of electrical attraction a charged droplet can pull uncharged droplets to itself from a considerable distance. The capture coefficient should be therefore much larger than for gravitational sweep-out alone.

An equation developed in 1952 was used to calculate the coalescence growth of a charged solution drop of radius, r_s', capturing neutral fog droplets. The collection coefficient, ε, is for electrically charged droplets:

$$\varepsilon = \left(\frac{1}{r_s'}\right)^2 \left[\frac{45\lambda r^2 Q^2}{16\gamma g(r_s'^2 - r^2)}\right]^{2/5} \tag{7}$$

where

λ = the induction factor $\sim$ 1
Q = charge on the solution drop
γ = density of the solution drop
g = acceleration due to gravity

In this equation the inertia of the droplets and the hydrodynamic curvature of their trajectories are neglected. Thus, this equation holds only for highly charged drops. "As r_s' increases with growth, the charged drop formula becomes inaccurate and the inertia of the droplets and curvature of the streamlines near them has to be taken into account" (Fuchs (1964). This error is present in the following calculations and the collection coefficient, as calculated, may be in error by as much as a factor of three at the low charge-to-mass ratios. The calculated collection coefficient may also be in error due to an effect on the collection coefficient of a drop falling in a spray of other like sized and charged drops. Because the effects of wake interaction are neglected, single drop calculations or even single drop experimental data probably only approximate the collection coefficients of a family of drops in a spray.

Details of Drop Growth Calculations

A digital computer program was coded to calculate the growth of treatment drops as they fell through fog. For an elapsed time, the mass gained (or lost) by the drop by water vapor diffusional growth (or evaporation) was added to the mass gained by accretion of fog droplets. The mass gained or lost by diffusion was calculated using Fukuta's equation. The mass gained by accretion was dependent on the Smolochowskian capture coefficient for an uncharged drop and on "ε" for a charged drop.

Since the effective cross-sectional area for an uncharged drop is derived from equation 4 as:

$$a_u = \pi E(r_s' + r)^2 \tag{8}$$

and the effective cross-sectional area swept out by the charged drop is computed by Cochet (1952) as

$$a_c = \pi \varepsilon r_s'^2 \tag{9}$$

the Smolochowskian capture coefficient, E, was corrected to E' where

$$E' = \left(\frac{r_s' + r}{r} \right)^2 E \tag{10}$$

so that E' and have the same physical significance. Values of the uncharged collision efficiencies reported by Davis, et al. (1970) and by Mason (1957) with 5μ radius droplets were approximated by

$$E' = 35\, r_s' \tag{11}$$

The error in this relation is small compared to diffusional growth and growth by accretion of charged drops between 10^{-3} and 10^{-2} centimeters.

The mass gained by a treatment drop in time t by accretion is

$$\int_0^t dm = \int_0^t (LWC) e\, \pi r_s'^2 V_o\, dt \tag{12}$$

where

(LWC) = the liquid water content which is the number of fog droplets per cm^3 times the mass of a fog droplet.

e = ε if the drop is charged, E' if uncharged.

$\pi r_s'^2$ = the cross-sectional area of the drop.

V_o = difference in fall velocities of the drop and droplets

t = time

The difference in fall velocities of the drop and droplet is

$$V_o = V_s - \frac{2r^2\gamma g}{9\eta} \tag{13}$$

where

V_s = terminal velocity of the drop

$\frac{(2r^2\gamma g)}{9\eta}$ = terminal velocity of the fog droplets calculated by Stoke's equation

The terminal velocity of drops of radii larger than 10 microns cannot be accurately determined by Stoke's equation because the inertia term in the fluid mechanic equation can no longer be neglected. The results of many experimental investigations of the rate of settling of aerosol particles in air were summarized by Fuchs (1964, p.33). An empirical equation was used which fit these data for radii between 10 and 125 μ .

$$V_s = 10^{5.5} r_s'^{1.8} \tag{14}$$

where V_s and r_s' are expressed in centimeters.

The maximum charge that a drop can be given without breaking is called the Rayleigh limit. At the Rayleigh limit

$$Q^2 = 16\pi\sigma' r_s'^3 \text{ (esu)} \tag{15}$$

where σ is the surface tension of the drop. Table 1 shows the maximum charge that can be carried by various sized drops.

Table 1.

Charge Per Drop at Rayleigh Limit

Radius cm	Charge squared $(esu)^2$
10×10^{-4}	3.67×10^{-6}
20×10^{-4}	2.94×10^{-5}
40×10^{-4}	2.35×10^{-4}
100×10^{-4}	3.67×10^{-3}

The above equations were used to calculate the growth of a drop of given initial radius and charge. The initial charge was chosen to equal the Rayleigh limit in the charged drop calculations. For each time step the computer calculated the mass gained by diffusional growth and by accretion.

The computer added these masses to the initial mass, computed a new radius, calculated a new collection coefficient and other parameters which change in value as the drop grows, and then repeated the process until the drops were calculated to have fallen more than 200 meters. The growth was calculated by holding the relative humidity, liquid water content, and fog droplet radius constant for the entire 200 meters of fall. The fog droplets were considered to be monodisperse. The time integral was varied stepwise from 0.05 seconds to 60 seconds. The small time step was used initially because it was necessary to calculate precise values for the small drops; as the drop grew to a larger size and was diluted by the liquid and vapor water, larger integral times were possible.

Results of the Drop Growth Calculations

Figures 1-3 show the growth of 40-μ-radius drops of charged and uncharged hygroscopic agent and charged water falling in air with a relative humidity of 98% and containing 0.2 g/m^3 LWC of 5 μ droplets. Also shown in these Figures are the sweep area of the drops, the fall distance, mass of liquid water collected, and the mass of water vapor absorbed or evaporated.

VISIBILITY

Removing Fog Droplets

Sweep area, a, is the effective cross-sectional area under a falling drop.

$$a = \pi r_s'^2 e$$

The probability of sweep out can be calculated, assuming that the course of one droplet is not affected by the others.

If "a" is the effective cross section of each drop and A is the area of a horizontal plane upon which the drops impinge and X, the number of drops, is such that

$$Xa = A \tag{16}$$

the probability that a single drop will hit a specified point in A is

$$p = \frac{a}{A} = \frac{1}{X} \tag{17}$$

The probability, q, a single drop will not hit a specified point in A is

$$q = 1 - p = 1 - \frac{1}{X} \tag{18}$$

The probability that all X drops will not hit a specified point in A is therefore

$$q^X = (1 - \frac{1}{X})^X \tag{19}$$

For large values of X this is approximated by

$$q^X \approx e^{-1} \approx 0.3679 \tag{20}$$

The probability that a point will be hit by at least one of the X drops is therefore

$$1 - q^X = 1 - (1 - \frac{1}{X})^X \approx 1 - e^{-1} \approx 0.6321 \tag{21}$$

If there are Y drops instead of X, the definition of p remains the same but the exponent becomes Y. The probability that a point will be hit by a drop becomes therefore

$$1 - (1 - \frac{1}{X})^Y \approx 1 - e^{-Y/X} \quad \text{(for large Y)} \tag{22}$$

Hence by sweep out alone, one cannot be certain of removing all fog droplets with less than an infinite amount of material.

If the assumption is made that the calculations for a single drop are realistic for a monodisperse spray of multiple drops, then the fog clearing potential of the spray can be easily calculated.

The probability that a point will be hit by at least one drop is

$$P = 1 - e^{-Y/X} \tag{23}$$

Calculations were performed where the number of drops was chosen such that X=Y, with X calculated using the minimum sweep for a single drop falling 200 meters through a fog of 5 μ droplet radius and 0.2 gram per cubic meter LWC. Table 2 shows these results for drops of10, 40 and 100 μ initial radius. At these "standard dosages" 63% of the droplets would be swept out.

Table 2.

Solution Drops Charged at the Rayleigh Limit Sufficient to Sweep Out 63% of the Fog

Initial Radius, μ	Minimum Sweep per drop, cm^2	Drops per cm^2	Gallons per acre	Grams per m^2
10	2.95×10^{-4}	3.4×10^{3}	0.153	0.195
40	9.0×10^{-4}	1.1×10^{3}	3.16	4.04
100	1.9×10^{-3}	5.3×10^{2}	24.0	30.4

Since $P = 1 - e^{Y/X}$, three times the dosage shown in Table 1 would result in sweeping out 95% of the fog droplets.

Visibility Improvement

We have calculated the fall, growth and sweep area of one drop and the probability that a droplet will be hit by at least one drop. If we assume this drop can represent the average of all of the drops falling from a monodisperse spray treatment of a fog clearing operation, then we can calculate the improvement of visibility through the fog.

Four simplifications were made in order to ease the calculations of visibility improvement.

1. The liquid water content (LWC) was held constant at 0.2 g/m^3 for all drop growth calculations. Actually, in multiple treatments of a patch of 0.2 fog, the LWC would decrease after each treatment; thus the sweep area of each drop would not decrease as much (see Figures 1-3).

2. The percentage of fog droplets larger than 5 micorns in radius swept out by the treatment drops was the same as the percentage of 5 micron droplets swept out. Since ε is proportional to $[r^2/(r_s'^2 - r^2)]^{2/5}$ and sweep is proportional to ε, the percentage of the larger droplets swept out will actually be higher than 95%.

3. Almost all of the LWC of the fog is contained in those droplets larger than 5 microns in radius and the growth of the treatment drop will not be significantly affected by accretion with those fog droplets smaller than 5 microns. When this is not the case, this simplification would result in too large of a calculated sweep area.

4. Evaporation of fog droplets due to drying of the air by the hygroscopic agent was ignored.

For charged drops the sweep out is

$$a = \varepsilon \pi r_s'^2$$

since

$$\varepsilon \text{ is proportional to } \left(\frac{r^2}{r_s'^2 - r^2} \right)^{2/5}$$

$$a_i = a_5 \left| \frac{r_i^2 (r_s'^2 - 25)}{25 (r_s'^2 - r_i^2)} \right|^{2/5}$$

when $r_s' >> 5\mu$

$$a_i = a_5 \left(\frac{r_i}{5} \right)^{4/5} \tag{24}$$

where

a_5 = sweep on a 5 micron radius fog droplet

a_i = sweep on a fog droplet of radius r_i

The term "standard dose" will mean the quantity of treatment agent such that the sweep times the number of drops is equal to the target area, X = Y (see Table 2).

Now three standard doses will be sprayed onto a fog and the increase in visibility will be calculated.

Consider the probability of being swept out by three standard dosages as a function of fog droplet size. Since $P_i = 1 - e^{-Y/X_i}$ and $X_i = A/a_i$, then $P_i = 1 - \exp(-3a_i/a_5)$ when Y is chosen such that $Y = 3X_5$.

Table 3.

The Probability of Being Swept Out

r_i (μ)	a_i/a_5	i
1	.276	.56
2	.480	.76
3	.665	.86
4	.837	.92
5	1.000	.95

Table 3 shows the values of P for droplet radii 5 micron and smaller. The number of droplets of any size which remain after a treatment with three standard dosages is 1 - P_i (e.g., 0.14% of the 3 micron droplets remain).

The visibility in a fog can be calculated by an equation derived by Trabert (1901).

$$V = \frac{C\Sigma N_i r_i 3}{(LWC)\Sigma N_i r_i^2} \qquad (25)$$

where

V = the visibility in the fog.
C = a numerical scattering factor, 2.6.
N_i = the concentration of droplets of radius r_i.

For many fogs which have very few droplets smaller than 5 microns, the visibility would be 20 times greater after sweeping out 95% of all droplets 5 μ and larger. Another way of saying this is, V would be inversely proportional to the treated fog LWC.

For those fogs which have small droplet sizes we used the data of May (1961). In this careful study, the sampling of fog droplets was done with a cascade impactor (using gelatin coated slides); droplets of radii as small as 0.4 microns were measured, and corrections were made to the counts of droplets of radii smaller than 1 micron radius to compensate for the collection efficiency of the impactor slides. Although May did not report the droplet size distribution, per se, he found that in 16 cases out of 28 the equation of Best (1951) fit his data. By use of a computer or a calculator the size distributions can be easily calculated. The Best equation is

$$1 - F = \exp\left[-(2r/a)^n\right] \qquad (26)$$

where

F = the fraction of the volume of water in the air comprised of droplets of radius less than r
a and n are constants

The size distributions of 6 of the 16 fogs (see Table 4) reported on were calculated. The 6 were chosen to cover the limits of a, n, LWC, and visibility. The number of droplets in each size range was reduced by 95% or less using Table 3 to compute the treated fog droplet concentration and distribution. Trabert's equation was then used to compute the visibility before and after treatment. Table 4 shows May's data and Table 5 the calculated values. The calculated increases in visibility varied from a factor of 3 to a factor of 20. The fogs with many small fog droplets of less than 0.6 microns showed the smallest improvements in visibility. These small droplets would rapidly evaporate if the treatment agent reduced the relative humidity, unless they had a large hygroscopic nuclei; in these cases even the highly charged hygroscopic

drops would be relatively ineffective. The majority of fogs, however, should have large visibility improvements after treatment. Table 5 shows the results of the calculations.

Table 6 shows the relative growth of a water drop charged at the Rayleigh limit falling through a fog of 5 μ radii droplets and 98% RH. The smaller drops have a higher efficiency but a longer fall time. At some point a longer fall time will negate the increase in efficiency (see Figure 4.).

Table 4.

Data of May

Fog	Date	Visual Range (m)	Drop radius range (μ)	Number median radius (μ)	Volume median radius (μ)	Number of drops per cc	LWC g/m^3	n	a
1	19Feb57	200	0.5-80	1.1	25	165	0.130	1.54	79.8
2	3Apr57	300	0.6-160	1	43	54	0.046	1.53	112.7
3	6Feb59	200	0.5-15	0.8	3.6	360	0.007	1.38	10
4	25Jan60	160	1.3-21	10	12	23	0.13	5.58	26.5
5	17Oct60	160	0.5-32	1.4	18	39	0.117	3.40	39.7
6	13Dec60	75	0.8-22	1.2	6.3	982	0.102	2.18	16.4

Table 5.

Calculated Visibility Increase for Fogs
Treated with Charged, Hygroscopic Drops

Fog	Visibility, meters		V_{tr}/V_{untr}
	treated	untreated	
1	5,770	700	8
2	24,800	2,700	9
3	6,240	2,000	3
4	9,200	460	20
5	12,900	690	19
6	1,800	270	7

Table 6.

Water Drops Charged at the Rayleigh Limit
Falling 200 Meters in a Fog of 5μ Droplets and 98%RH

Initial radius (μ)	Mass of fog collected per mass of agent (g/g)	Time of drop (sec)
12.5	234.0	1,200
25	51.0	600
40	18.4	400
50	11.3	330
100	2.5	163
200	.57	63

Discussion of Results of Visibility Calculations

The visibilities reported by May and those calculated by Trabert's equation were not in agreement. The reported visibilities were of lamp posts and were thus based on an arbitrary standard; the relative visibilites (ratio of reported to calculated) were in better agreement. Since the visibility improvement was a ratio of the calculated treated vs. calculated untreated, it should be a good measure of improvement.

Of the six fogs shown in Table 4, the particle size distribution of the 25 January 1960 fog is most typical of advection type fogs. Treating this type of fog increased the visibility by a factor of 20. The particle size distribution of the 6 February 1959 fog is somewhat typical of a haze (Green and Lane, 1964, p. 4). Since the LWC of this fog was only 0.007 gram per cubic meter and the computer calculations of drop growth and sweep used o.2 gram per cubic meter, the value of sweep used to calculate the visibility improvement was too small. For this fog (haze) the calculated improvement in visibility was 300 %. Even this small improvement could be socially useful in smog abatement.

CONCLUSIONS

The use of urea-ammonium nitrate-water, hygroscopic solution drops, electrically charged to the Rayleigh limit, will provide a method of fog dispersal wherein reasonable dosage rates would be sufficient to improve visibility by removing 95% of the fog droplets larger than 5 μ radius.

- - - - -

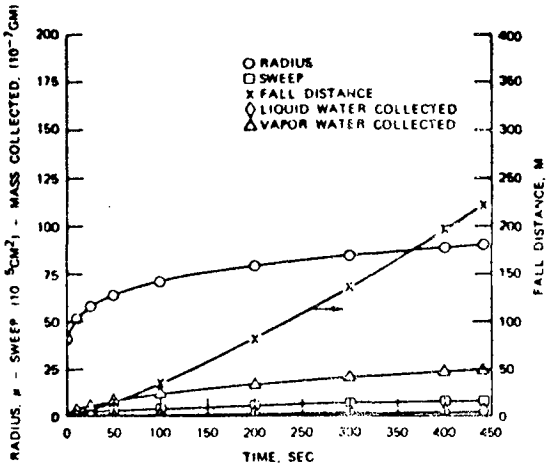


FIG 1. THE GROWTH OF AN UNCHARGED DROP OF UREA–AMMONIUM NITRATE SOLUTION FALLING IN A FOG OF 5μ RADIUS DROPLETS AND 98% RH.

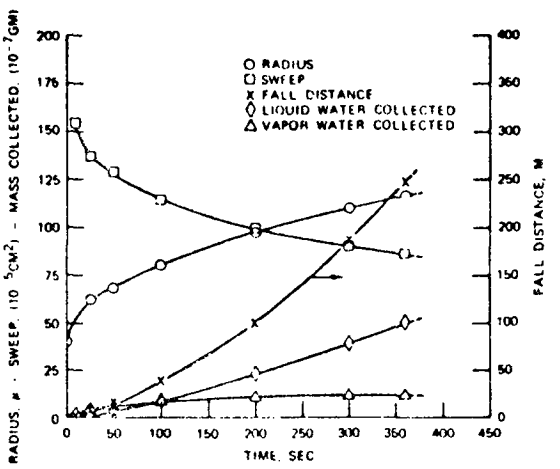


FIG 2. THE GROWTH OF A DROP OF UREA–AMMONIUM NITRATE SOLUTION CHARGED AT THE RAYLEIGH LIMIT FALLING IN A FOG OF 5μ RADIUS DROPLETS AND 98% RH.

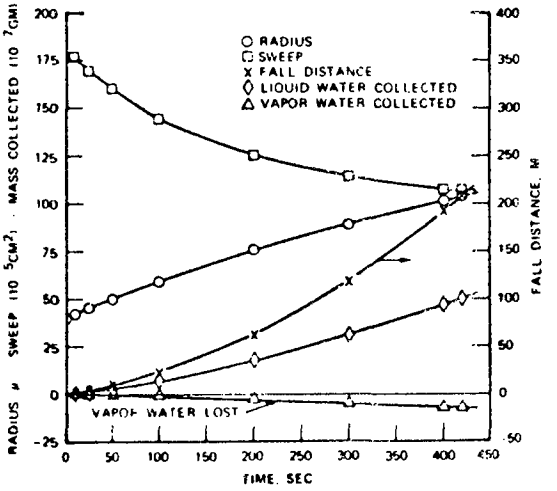


FIG 3. THE GROWTH OF A WATER DROP CHARGED AT THE RAYLEIGH LIMIT FALLING IN A FOG OF 5μ RADIUS DROPLETS AND 98% RH.

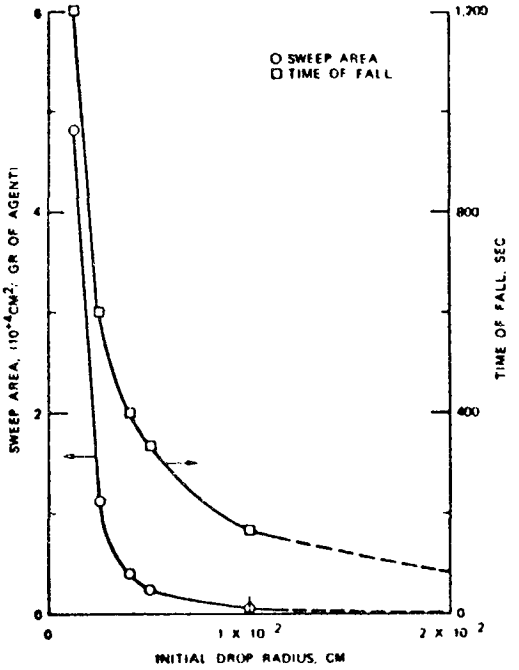


FIG 4. WATER DROPS CHARGED AT THE RAYLEIGH LIMIT FALLING 200 METERS IN A FOG OF 5μ RADIUS DROPLETS AND 98% RH.

REFERENCES

Best, A. C., 1951: Drop-size Distribution in Cloud and Fog, Quart. J. Met. Soc., 77, p. 418-426.

Blomerth, E. A., R. S. Clark, et al., 1970: Project Foggy Cloud I, Naval Weapons Center TP 4929, 51 pp.

Clark, R. S., L. A. Burkardt, J. W. Carroz, 1971: Properties of Ammonium Nitrate-Urea-Water Hygroscopic Reagent for Warm Fogs, Naval Weapons Center TP 5190, 26 pp.

Cochet, R., 1952: L'evolution d'une gouttelette d'eau chargee dans un nuage a' temperature positive, Annales de Geophysique 8, 1, p. 33-54.

Davis, M. H., J. D. Klett, and M. Neiburger (1970) "Collision Efficiencies of Cloud Drops at Small Reynolds Numbers," Conference on Cloud Physics, PREPRINTS, Ft. Collins, Colorado, 115-116.

Fuchs, N. A., 1964: The Mechanics of Aerosols, Pargamon Press, 408 pp.

Fukuta, Norihiko, L. W. Walter, 1970: Study of Basic Theories of Water Condensation, Naval Weapons Center TP 4904, 49 pp.

Green, H. L., W. R. Lane, 1964: Particulate Clouds: Dusts, Smokes and Mists, Van Nostrand Co. 471 pp.

Langmuir, I., 1961: Supercooled water droplets in rising currents of cold saturated air. The Collected Works of Irving Langmuir, 10, 199-334.

Mason, B. J., 1957: The Physics of Clouds, Oxford University Press, Inc., New York, 424 pp.

Maxwell, J. C., 1879: On stresses in rarified gases arising from inequalities of temperature. Phil. Trans., 170, 231-256.

May, K. R., 1961: Fog-droplet sampling using a modified impactor technique. Quart. J. R. Meteor. Soc., 87, No. 374, 535-548.

Rooth, C., 1957: On a special aspect of the condensation process and its importance in the treatment of cloud particle growth. Tellus, 9, 372-377.

Trabert, W. 1901: Die Extinction des Lichtes in einem truben Medium (Sehweite in Wolken)., Meteor. Z., 18, 518-520.

Wright, T. L., R. S. Clark, & Pierre St.-Amand, 1972: Foggy Cloud III, Phase I, NWC TP 5297, Naval Weapons Center, China Lake, California 93555, 68 pp.

- - - - -

MINICOMPUTER PROGRAM TO PREDICT FOG BREAK-UP TIMES

Harold E. Cronin

Naval Weapons Center
China Lake, California

ABSTRACT

A minicomputer program is used to compute and print the times for the most rapid, the 25%, the most probable, the 75% and the slowest clearing categories, after inputting time of sunrise and fog thickness. The tables thus generated are helpful in judging the success of fog modification tests.

BACKGROUND

For several years the Earth and Planetary Sciences Division of the Naval Weapons Center, China Lake has had a program in experimental modification of warm fogs. Hygroscopic solutions have been sprayed from aircraft, and also charged particles, dry powders, and pyrotechnically generated nuclei have been tried.

STATEMENT OF PROBLEM

In evaluating the results of the tests, some confusion may arise from the fact that the fog will generally clear naturally at sometime during the day. The earlier in the day that one is able to clear the fog, the more likely it is that the results of the test were due to the treatment used and not because of natural break-up processes. A method of predicting the time of fog-breakup is needed, in order to make judgements as to the validity of the test, and may help to evaluate if one type of treatment is better than another.

DISCUSSION

Although there will be some variations at each location due to peculiarities of local conditions, a means of making an assessment can be suggested. A graph entitled "Plot of Number of Hours of Sunshine Necessary for Breaking Varying Thicknesses of Cloud at Indicated Localities" as found in HANDBOOK OF METEOROLOGY (Berry, Bollay, and Beers, NavAer 50-1lOR-42, p.735), shows data taken at Boston, San Antonio and San Diego. This is reproduced as Figure 1.

The straight line least squares fit of the points indicates a relationship of one hour of sunshine clearing 120 meters of fog, or very close to 400 feet of clearing per hour. Those points above the center line are due to more rapid clearing than the average, and those below the line are due to slower than average clearing. Visual examination of the points indicate that there is a greater inclination for both persistence and variation in the fogs at Boston and San Antonio than those of San Diego. Also noted is the tendency for the points to group at 1, 2 and 4 hours, probably due to taking observations "on the hours".

If a line is drawn to connect the extreme points above the average line (X2), then the points of "most rapid clearing" (X0), are found; similarly, if the extreme points below the average are connected (X4), the "slowest clearing" points are found. By taking the average between the line of most rapid clearing and the mean, the 25 percentile line is determined (X1), and similarly the average between the mean and the slowest clearing line gives the 75 percentile line (X3). One can title these: time for most rapid clearing, time for 25% of cases, average time to clear, time for 75% of cases and slowest time for clearing. Thus the inputs necessary to make the determination are the thickness of the fog (B) and the time of sunrise (C). A comparison can then be made with test results to make a judgement of the effectiveness.

PROGRAM

It is convenient to be able to print out a table of the various times of clearing, a job which is well suited for a minicomputer. The computer used for this program is the PDP-8, with 4K memory size.

The program given below is written in FOCAL*(Fig. 2). For those who are not familiar with FOCAL*, it is a BASIC**-like language. The line numbers are followed by a command (abbreviated to the first letter) which tells the computer the desired operation to perform. The commands used are: A for ask, C for comment, T for type, S for set, QUIT for end of program, and FITR ( ) finds the integer part of a number. A * indicates multiplication, a / is division, and ! is for line feed, carriage return. The "GO" command causes the program to run. It asks for time of sunrise (B) and thickness of the fog (C) in feet. After these are typed in from the keyboard, it computes and prints out the times for rapid clearing, 25%, most probable, 75%, and slowest clearing (Fig. 3). A judgement can then be made of the validity of the results of a test.

*FOCAL - Trade mark of Digital Equipment Corp.

**Trademark, Dartmouth College

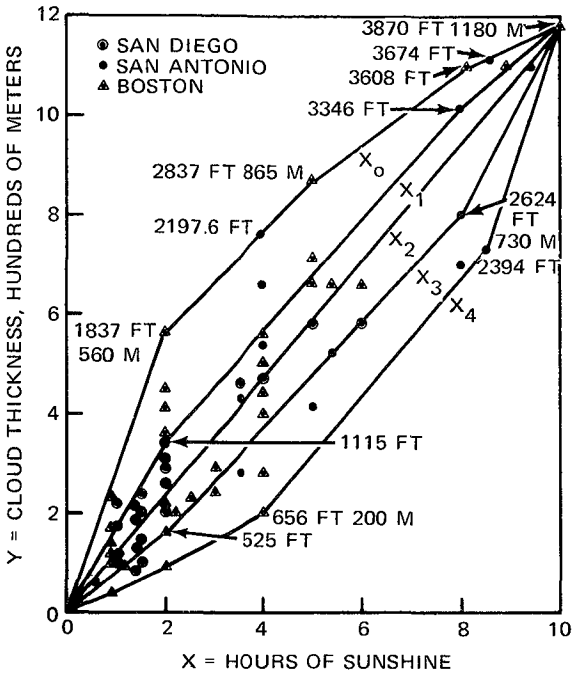


Figure 1.

"Plot of Number of Hours of Sunshine Necessary for Breaking Varying Thicknesses of Cloud at Indicated Localities". (After Berry, Bollay and Beers).

RESULTS AND CONCLUSIONS

In making the computations, the program first changes time into hours and decimal parts. Next the values of X0, X1, . . . are set to the slopes near the origin. The program then "ripples through" a series of IF statements, changing the values of the X's to reflect the changes in slopes indicated. A value within the range of X transfers to print out the headings, add the time of sunrise to the computed time, reconvert hours and decimal parts to hours and minutes and print out the resultants. If the fog thickness is greater than the maximum IF value, control transfers to print out a "PROBABLY WON'T CLEAR" message.

Figure 3 shows values obtained in a typical run. Note that if the value of sunrise is input at 0000, then the printed values will be exactly the "Hours of Sunshine" shown in Figure 1. In this manner, a check can be made that the computed values agree with those shown on the plot.

```
 WRITE ALL
C-FOCAL,1969

01.02 C-  PROGRAM TO PREDICT FOG BREAK-UP TIMES
01.10 T "TIME OF SUNRISE"; A B
01.20 T "FOG THICKNESS AT SUNRISE IN FEET"; A C
01.30 S H=FITR(B*.01); S M=B-(H*100); S M1=M/60; S T=H+M1
01.40 S X0=C/918;S X1=C/558; S X2=C/387;S X3=C/263; S X4=C/164
01.50 IF (C-525)6.1, 6.1, 1.6
01.60 S X3=2+(C-525)/350
01.70 IF (C-656) 6.1, 6.1, 1.8
01.80 S X4=4+(C-656)/386
01.90 IF (C-1115) 6.1, 6.1, 2.1

02.10 S X1=2+(C-1115)/372
02.20 IF (C-1837) 6.1, 6.1, 2.3
02.30 S X0=2+(C-1837)/334
02.40 IF (C-2394) 6.1, 6.1, 2.5
02.50 S X4=8.5+(C-2394)/984
02.60 IF (C-2624) 6.1,6.1,2.7
02.70 S X3=8+(C-2624)/623
02.80 IF (C-2837) 6.1, 6.1, 2.9
02.90 S X0=5+(C-2837)/257

03.10 IF (C-3346) 6.1, 6.1, 3.2
03.20 S X1=8+(C-3346)/262
03.30 IF (C-3608) 6.1, 6.1, 3.4
03.40 S X0=8+(C-3608)/131
03.50 IF (C-3870) 6.1, 6.1, 8.1

06.10 T "RAPID CLRNG  25%CHANCE  MOST PROB  75%CHANCE SM. CHANCE",!
06.20 S X(5)=T+X0;S X(6)=T+X1;S X(7)=T+X2;S X(8)=T+X3;S X(9)=T+X4
06.30 FOR I=5,1,9; DO 7

07.10 S U(I)=FITR(X(I))
07.20 S W(I)=X(I)-U(I)
07.30 S V(I)=W(I)*60

08.05 T %2.0,U(5),":",V(5),"     ",U(6),":",V(6),"     ",
08.06 T %2.0,U(7),":",V(7),"     ",U(8),":",V(8),"     ",
08.07 T %2.0,U(9),":",V(9),!!
08.08 QUIT
08.10 T "PROBABLY WON'T CLEAR",!!; GOTO 1.1
*
```

Figure 2.

```
 GO
TIME OF SUNRISE:0600
FOG THICKNESS AT SUNRISE IN FEET:1000
RAPID CLRNG  25%CHANCE  MOST PROB  75%CHANCE SM. CHANCE
  7:  5       7: 48       8: 35       9: 22     10: 54

*GO
TIME OF SUNRISE:0615
FOG THICKNESS AT SUNRISE IN FEET:2200
RAPID CLRNG  25%CHANCE  MOST PROB  75%CHANCE SM. CHANCE
  9: 20      11: 10      11: 56      13:  2     14: 15

*GO
TIME OF SUNRISE:0556
FOG THICKNESS AT SUNRISE IN FEET:1600
RAPID CLRNG  25%CHANCE  MOST PROB  75%CHANCE SM. CHANCE
  7: 41       9: 14      10:  4      11:  0     12: 23

*GO
TIME OF SUNRISE:0622
FOG THICKNESS AT SUNRISE IN FEET:2800
RAPID CLRNG  25%CHANCE  MOST PROB  75%CHANCE SM. CHANCE
 11: 15      12: 54      13: 36      14: 39     15: 17

*GO
TIME OF SUNRISE:0610
FOG THICKNESS AT SUNRISE IN FEET:700
RAPID CLRNG  25%CHANCE  MOST PROB  75%CHANCE SM. CHANCE
  6: 56       7: 25       7: 59       8: 40     10: 17

*
```

"Examples of Fog Break-up Times Given by Computer Runs"

Figure 3.

AIRBORNE JET SEEDER SOLUTION BURNER

John Carroz

Naval Weapons Center
China Lake, California

ABSTRACT

This paper describes the Naval Weapons Center Airborne Jet Seeder design and nuclei output. The jet seeder consists of a simple burner and a more complex solution delivery system. The nuclei counts per gram of silver iodide were very high in relation to other nuclei generators at the warmer nucleating temperatures (-8^{0}C and warmer).

INTRODUCTION

As part of a cold cloud modification subsystem, the Naval Weapons Center has designed, developed, and tested an airborne jet seeder (AJS), which operates on the ramjet principle. Under approximately 120-lb/in^{2} pressure, a swirl nozzle sprays a solution of silver iodide, ammonium iodide and acetone into a chamber, where it is mixed with air and burned. Users can vary nozzle size and solution concentration to optimize the count for particular missions.

The AJS operated successfully at various speeds and altitudes when flight-tested with a Cessna 337 aircraft. Acetone solutions containing up to 10% of silver iodide ignited and burned. Solutions of 10% lithium chloride dissolved in methanol and acetone burned, also.

This paper covers the design and the nuclei output of the AJS.

THE AJS DESIGN

The AJS is essentially a ramjet device. The classical ramjet engine, however, is designed to produce maximum thrust, whereas this application is designed to finely atomize and burn a solution.

Before commencing the actual designing of the AJS, ramjet technology was reviewed with a view to relating it to the combustion of the solution of silver iodide, ammonium iodide and acetone required for cloud seeding. Although existing ramjet designs were found unsuitable for burning acetone solutions, a couple of years of engineering effort were saved by using the basic principles of ramjet technology.

The device consists of a solution tank, a high-pressure nitrogen tank, a burner, and several minor components shown in Figure 1.

The AJS is 75 inches long and weighs 106 pounds empty and 161 pounds when filled with a 10% silver iodide solution. Described below are the three main sections: the nose section, the center section, and the tail section.

Nose Section

The nose section holds all the components required to feed the solution to the burner at an elevated pressure. A description of each nose section component, along with its function, follows.

Nitrogen pressure tank. The 200-in^3 steel tank, manufactured to military specifications for high-pressure air and proof-tested at 4,500 lb/in^2, is filled with nitrogen at 2,500 lb/in^2 maximum pressure. The nitrogen serves to maintain the required pressure in the solution tank, which is located in the center section. The nitrogen tank has been in production for the Department of Defense for several years.

Gas regulator. The regulator reduces the pressure of the gas flowing from the nitrogen pressure tank to the pressure desired for the solution tank. This is usually 120 lb/in^2.

Check valve. The check valve prevents the acetone solution from backing into the regulator or the pressure tank.

Relief valve. If the pressure in the solution tank rises above 150 lb/in^2, the relief valve opens to relieve the excess pressure.

Solenoid valve. The solenoid valve regulates the on and off flow of the solution. A 24-volt power supply is required to keep the valve open; it closes when the power is off. The valve has polypropylene inserts for acetone resistance.

Stainless steel tubing. Standard tubing and fittings permit the nitrogen and solution to flow to and from the various components. Two valves not shown in Figure 1 are manually operated to fill the AJS with nitrogen and solution.

Nose cover. The nose cover protects all the nose section components.

Center Section

The center section consists of the following components:

Solution tank. A specially made, 7-gallon stainless steel tank, pressure-tested to 300 lb/in^2, holds the acetone solution. The solution tank is pressurized (usually at 120 lb/in^2) by the nitrogen tank in the nose section. The solution is transported through an outlet at the bottom of the tank.

Pipes and baffles. Baffles stabilize the solution tank when it is only partially full. A stainless steel pipe supports the baffles and also adds strength to the tank. The solution passes from the solenoid valve in the nose section to the burner nozzle through tubing inside the pipe.

Strongback. A strongback like the one used for Brighteye (an air-launched Navy illuminating flare) is strapped onto the tank with steel shipping bands.

Filling valve. A manually operated valve is used for filling and emptying the solution tank.

Tail Section

The tail section (shown in figure 1) houses the burner and is made up of the following major components:

Flame holder. The acetone solution from the solution tank is sprayed into the flame holder, vigorously mixed with a small amount of air, and ignited. The flame holder creates circulation zones in the air. The flame enters these zones and is circulated and spread to other parts of the burner. The flame holder is 4 1/2 inches in diameter and 8 inches long.

Flame tube. The flame tube is 6 inches in diameter and 18 inches long. After the acetone solution has been ignited and mixed with air in the flame holder, the flame enters the flame tube, where it is mixed with more air. The flame exits from the flame tube opening at the aft end of the AJS.

Nozzle. The pressurized acetone solution is sprayed into the flame holder through an industrial spray nozzle, which converts the liquid into small droplets. Since each drop forms a nucleus, the spraying is very important to the operation of the burner.

Inlet air scoops. Seven air scoops near the rear of the burner allow a calculated amount of air to enter. The area of the scoops was designed for operation at airspeeds between 50 and 200 knots.

Primary air passages. A small percentage of the air that enters the burner flows through the primary air passages into the flame holder.

Secondary air passages. Most of the air flows into the flame tube through the secondary air passages (which parallel the tube wall) and mixes slowly with the flame.

Igniter. An Auburn I-18 long-reaching spark plug starts the fire. It turns off automatically after ignition.

Igniter power supply. The igniter power supply, housed in a box attached to the tail section, uses a Model T coil and raises the 28-volt input to the several-thousand-volt output needed for the spark.

Flame indicator. (Not shown in Figure 2). A thermocouple inside the flame tube registers the flame temperature and feeds the data back to the aircraft cockpit. Since the flame can be seen at night, the flame indicator is needed only in daylight hours.

CHOOSING AN ATOMIZER

The most critical part of the AJS is the nozzle, or atomizer. It should produce solution drops small enough so that after the acetone vaporizes the radius of the silver iodide particles is not more than 0.2 micron (Finnegan 1971, St.-Amand 1971, Mathews 1972). Particles larger than that are larger than is necessary to nucleate the largest supercooled water drop

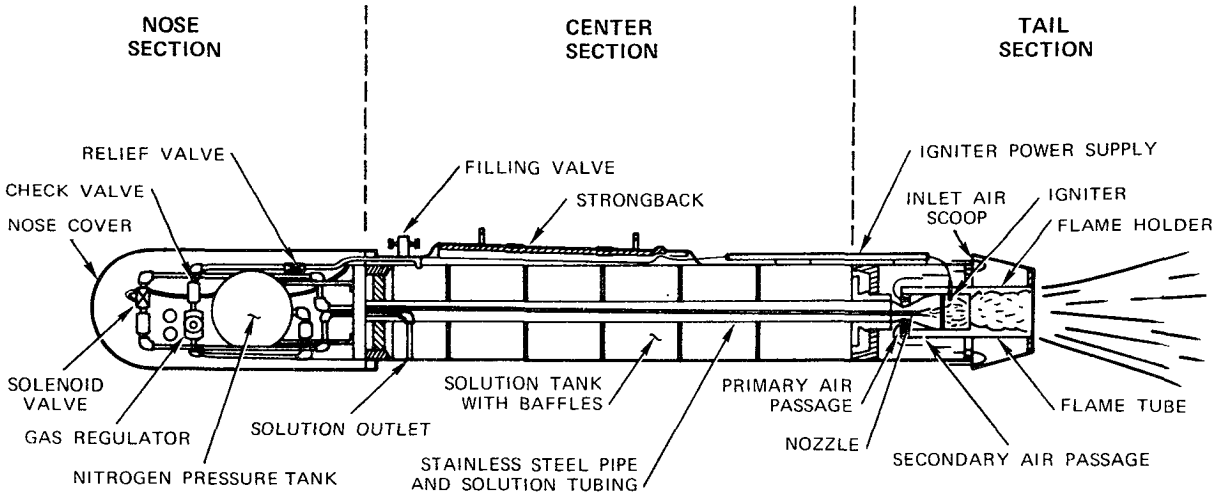


Figure 1.

Arrangement of the AJS

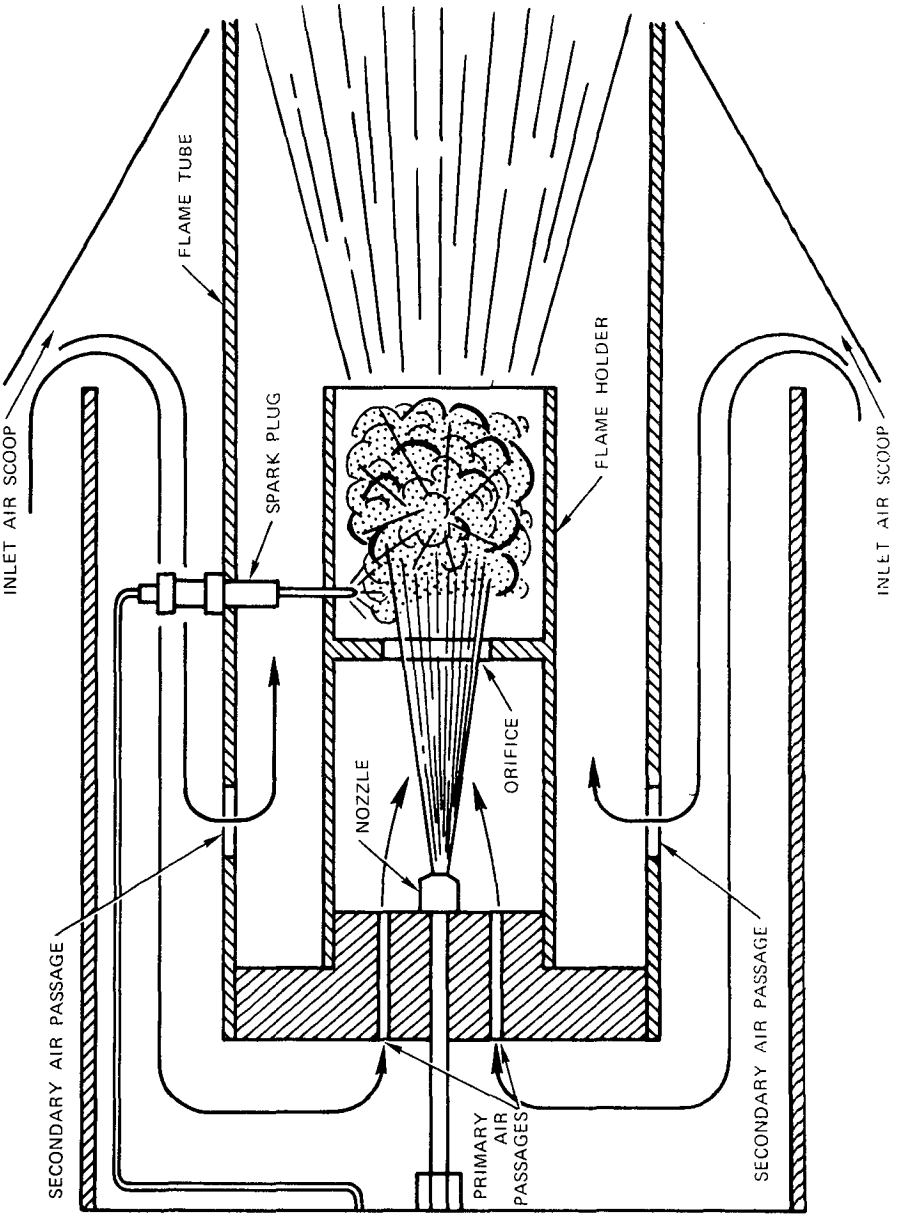


Figure 2.

AJS Burner

at the warmest freezing temperature, and since mass is proportional to the radius cubed, the larger particles would waste relatively large amounts of silver iodide.

There appear to be available at least three types of devices that can be used for atomizing a liquid into aerosol-size particles without also emitting larger particles: (1) an ultrasonic nebulizer with a piezoelectric crystal, (2) an oil smoke generator that uses a vaporization and condensation method and (3) an atomizer, described in by Litt and Swift (1972), that makes use of the surface tension of the liquid. To date we have not been able to use any of those types of devices for the AJS.

Another approach might be to use an air-blast (pneumatic) nozzle. This type of nozzle produces a very wide range of droplet sizes and requires a large quantity of gas. Because the small tank that supplies nitrogen for pressurizing the AJS's fuel could not carry a sufficient quantity for even a few minutes of spraying, an air compressor would be required. Use of a compressor, however, was not deemed feasible for the 7-gallon, 106-pound AJS.

A spinning disk atomizer was considered briefly. Although this type of atomizer produces a spray of uniform (although large) particles, it requires a relatively large power source to spin the disk. This method, also, was not deemed feasible for the AJS.

The atomizer finally chosen is a swirl nozzle. Swirl nozzles, which are the simplest type of atomizer, come in all sizes and shapes and are readily available from several commercial sources. Liquid is forced through tangential passages at the base of a conical chamber and swirls as it exits from a small orifice. At high pressures the spray converts into droplets with a wide distribution of sizes immediately after leaving the nozzle orifice. Tate and Olsen (1962), give the results of measuring the droplets produced by four Delavan swirl nozzles, which are similar to those used in the AJS.

Any droplets that hit the burner hardware before the acetone has vaporized and the ammonium iodide has decomposed will stick to the hardware and form a slag buildup. The spray must be directed into a cone with an angle small enough so that the droplets will not hit the hardware. Only nozzles with narrow spray angles are used for the AJS.

FUEL-TO-AIR RATIO

The design of the tail section (Figure 2) allows operation of the burner at varying air speeds with a fixed-size air inlet. Since the objective is cloud seeding, not propulsion, air-to-fuel ratios in excess of stoichiometry are used. This results in high nuclei output and cooler temperatures inside the burner. The measured inside temperatures were always lower than 700°C.

The design also allows maximum variability of the air-to-fuel ratio. In the flame holder, which protects the flame and maintains combustion, the ratio is lower than it is in the flame tube. If the velocity of the air in in the holder is too high, the flame is literally blown out the exhaust and further combustion ceases. The secondary air in the annulus supplies any additional oxygen needed for burning, and the excess air quenches the hot particles.

The flammable solution is sprayed into the flame holder and mixed with a small portion of the total airflow. A ring-shaped orifice increases the turbulence, which in turn aids the mixing. The solution ignites here, and the reaction between fuel and oxygen begins. If there is sufficient oxygen in the air in this portion of the burner, the fuel is oxidized to carbon dioxide and water in the flame holder, and merely mixes with the air in the flame tube and cools it. This would be the case for the highest aircraft speeds, which produce the highest total airflow through the burner. For lower speeds and airflow, the fuel does not react completely in the flame holder, and the hot gases continue to react with the additional oxygen in the air flowing through the flame tube.

Successful operation of the burner with solutions of silver iodide and acetone was achieved at air-to-fuel ratios between 11 and 129 (pounds per pound). At 129 for the total air-to-fuel ratio, the airflow splits so that the ratio in the flame holder is 15.2. At these ratios, one size of air inlet area should operate satisfactorily at aircraft speeds that differ by a factor of 10.

LABORATORY COUNTS OF NUCLEI

At both the Institute of Atmospheric Sciences, Rapid City, S. Dakota, and the Cloud Simulation and Aerosol Laboratory, Fort Collins, Colorado, counts of AJS nuclei were made to determine the cloud-seeding efficiency. Two independent counts do not usually agree; however, they do serve to check each other. Aside from the differences in the test equipment at the two facilities, the main difference in taking the counts was airspeed. Each facility used the highest possible wind-tunnel speed at its disposal; in the first series of tests, the maximum at Rapid City was 53 knots and at Fort Collins, 150.

In the first series of tests at Rapid City were conducted in March 1972 with six different burner configurations supplied by NWC (Blair, 1972). NWC then transported the burner to Fort Collins, where the same six tests were started in April and continued over a period of 6 weeks (Cloud Simulation and Aerosol Laboratory, 1972). The parameters used for tests are given in Table 1.

Table 1.

Parameters Used in Nuclei Counts at Rapid City and Fort Collins.

Test	Solution, %AgI	Nozzle No.	Pressure lb/in^2	Flow rate gal/hr
1	10	4.0B	92	3.37
2	15	2.5B	92	1.91
3	5	2.5B	100	1.91
4	5	2.0B	100	1.52
5	5	4.0B	100	3.37
6	5	4.0B	150	4.18

Figures showing the test results for each configuration are reported by Carroz and Durham (1972). In general, the counts were higher in the Fort Collins tests; in fact, at the warmer temperatures the counts for the 4.0B nozzle configurations were the highest ever measured at Fort Collins. For example, in test no. 1 the counts were about 8 x 10^{11} crystals per gram of silver iodide at -3°C, 1 x 10^{13} at -5°C, and 3 x 10^{14} at -7°C. The relative differences in counts at Rapid City for the six burner configurations were not the same as the relative differences in counts at Fort Collins. For example, all the 4.0B nozzles produced consistently higher counts at Fort Collins, whereas at Rapid City they did not.

In a second series of tests at Rapid City, the test set-up was modified such that an equivalent speed of 250 knots could be used. Since this second series at Rapid City is in progress, it will not be reported on now; except to note that when the air flow through the AJS is about the same at both test facilities, the warmest temperature for nucleation to occur is about -3°C in both places. In the first series of tests at Rapid City at 53 knots air speed, this temperature was -5°C.

The second series of tests at Fort Collins in September 1972 studied the effect of varying solution concentration and inlet-air flow (Cloud Simulation and Aerosol Laboratory, 1972). The results are shown in figures 3-6. The silver iodide concentration was lowered from the 5 and 10% levels used in the first series of tests to 1 and 2%. The air flow for some tests was reduced by covering four of the inlet-air scoops. The parameters used for tests are given in Table 2.

Table 2.

Parameters Used in Nuclei Counts at
Fort Collins for the Second Series of Tests

Test	Solution, %AgI	Nozzle No.	Pressure, lb/in^2	Flow rate, gal/hr	Inlet-Air Flow
1	1	4.0	92	3.37	Full
2	2	2.0	92	1.52	Full
3	2	4.0	92	3.37	Full
4	2	2.0	92	1.52	1/2
5	2	4.0	92	3.37	1/2

Testing of the 1% silver iodide solution at -10°C resulted in crystal counts below chamber resolutions. The 2% silver iodide solution gave reduced crystal counts much below those of series 1 for 5% and 10% silver iodide solutions (Figures 3 and 4). Changing the air flow greatly affected the output with the 4 GPH nozzle. With the 2 GPH nozzle, changing the air flow did not appear to affect the output. Work is in progress to determine why the output varies with different airflows (Figures 5 and 6).

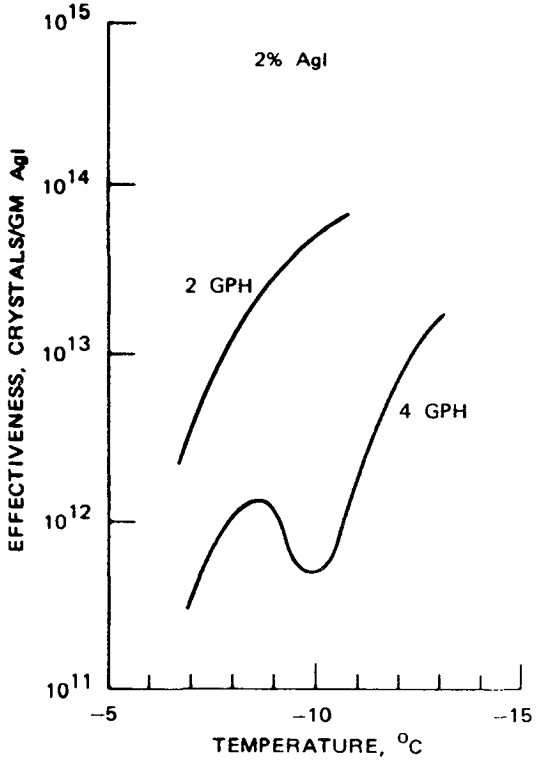


Figure 3.

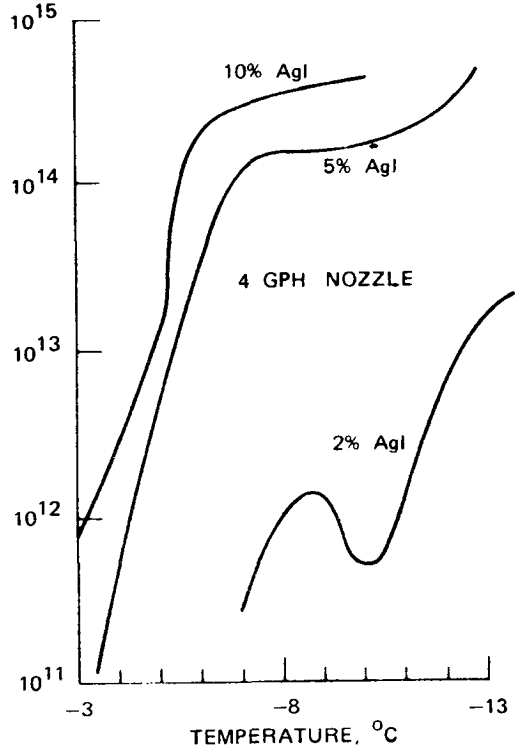


Figure 4.

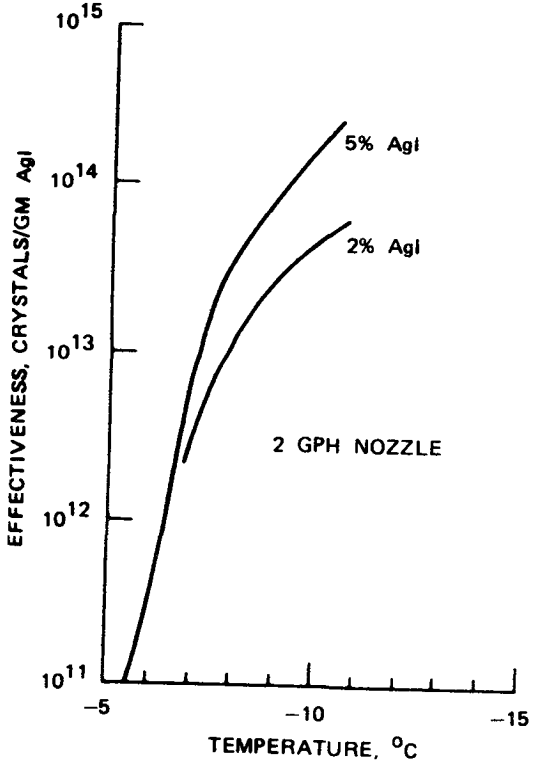


Figure 5.

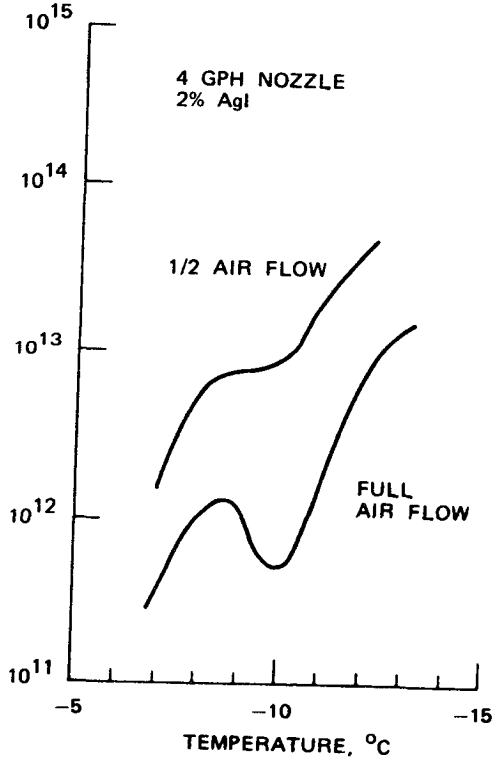


Figure 6.

The AJS was field tested first in seeding the cap cloud and associated shallow cumulus clouds over Elk Mountain in Southeastern Wyoming in February 1972. Later some limited testing was also conducted in seeding marginal cumulus clouds over the Sierras. In all of these tests, treated clouds glaciated rapidly. The AJS was equipped with a 2.0 GPH nozzle and burned a 5% AgI solution. The seeding aircraft usually seeded the target cloud at the $-5^{o}C$ temperature level at an indicated airspeed of 140 knots. Currently (Winter 1972/73) the AJS is being tested quantitatively in seeding rainbands that are approaching the coast near Santa Barbara, California; this testing has not been completed.

Testing is continuing and may clear up many of the present uncertainties. Fortunately, all the configurations yield counts high enough for cloud seeding. With the present design and knowledge, the AJS delivers enough nuclei to modify weather, and the users can vary the nozzle size and solution concentration to optimize the count to meet the requirements of a particular mission.

SUMMARY

The AJS functioned satisfactorily in all the aircraft tests and operated successfully at various speeds and altitudes. At the warmer temperatures the counts of nuclei were the highest ever measured at Fort Collins when the 4 GPH nozzle was used with 5 and 10% silver iodide solutions.

- - - - -

REFERENCES

1. Blair, D. N. Final Report-Nucleation Efficiency Tests Using the NWC Airborne Jet Seeder and Ground Burner, Institute of Atmospheric Sciences, South Dakota School of Mines, Rapid City, S.D., IAS, June 1972. 14 pp. (Report No. K-72-11).

2. Carroz, J. W. and M. F. Durham. Solution Burner for Weather Modification-Advanced Development of an Airborne Jet Seeder, Naval Weapons Center, China Lake, Ca., December 1972. NWC TP 5415 (In press).

3. Cloud Simulation and Aerosol Laboratory. Naval Weapons Center Airborne Jet Seeder Effectiveness Tests with NH_4I-AgI Solution. Colorado State University, Fort Collins, Col. CSAL, May 1972. 45 pp. (Report No. 7202C.) & October 72. 21 pp. (No.9-720937 to 10-72 1068).

4. Finnegan, W. G., Pierre St.-Amand, and L. A. Burkardt. "An Evaluation of Ice Nuclei Generator Systems," NATURE, Vol. 232(1971), p. 113.

5. Litt, M., and D. E. Swift. "The Babington Nebulizer: A New Principle for Generation of Therapeutic Aerosols," AMER REV RESPIRATORY DISEASE, Vol. 105(1972), pp. 308-10.

6. Mathews, L. A., and others. "Rate of Solution of Ice Nuclei in Water Drops and Its Effect on Nucleation," J APPL METEOROL, Vol. 11, No. 5 (August 1972), pp. 813-17.

7. St.-Amand, Pierre, and others. "Effects of Solubility on AgI Nucleation Effectiveness," J WEATHER MODIFICATION, Vol. 3(1971), pp. 106-10.

8. Tate, R. W., and E. O. Olsen. "Spray Drop Size," AMER SOC HEATING, REFRIG AIR-COND ENG J, Vol. 4 (1962), pp. 39-46.

- - - - -

PARTICLE SIZE AND NUCLEI ACTIVITY CHARACTERISTICS OF A LOW OUTPUT AgI GENERATOR

Briant L. Davis*
Donald N. Blair*
L. Ronald Johnson*
Pierre St. Amand**

*Institute of Atmospheric Sciences
South Dakota School of Mines and Technology
Rapid City, South Dakota 57701

**Earth and Planetary Sciences Division
Naval Weapons Center
China Lake, California 93555

ABSTRACT

A low output silver iodide generator using AgI-NH_4I-acetone solutions has been used as the source of aerosols for a particle size and nuclei activity analysis. Techniques of analysis include Fourier and variance-range profile analyses for particle size and size distributions; a wind tunnel/cloud chamber facility was used for the activity studies.

This generator produces crystallites having a short prismatic habit with diameters ranging from 0.09 μ to 0.17 μ as obtained from strain-corrected Williamson-Hall analyses. Strain-corrected estimates from particle size distributions give slightly larger values with a maximum of 0.30 μ for the 002 (c-axis) direction of one sample.

The aerosol produced by this generator is measurably more monodisperse than that obtained from other standard ground and airborne generators. The range in relative deviation from the mean, or coefficient of variance, σ/ε varies from 0.18 to 0.40 whereas for three selected ground and airborne generators taken from the literature these values range from 0.40 to 0.68.

The activity studies indicate that particles, obtained from solutions of high AgI concentration, yield the greatest nucleation efficiences in the -5°C to -10°C region. We also observe that in the -10°C to -20°C activity region aerosols produced at higher combustion temperatures are more active than those produced at the lower temperatures. The trend in the efficiency versus temperature curve bends over at about -10°C with a noticeably sharper "knee" than is observed for most other narrower size distribution for the aerosol.

The cloud chamber studies as well as the special series of x-ray chamber experiments indicate the existence of the previously observed -12°C "anomaly" for these aerosols. A comparison of activity and complexing

characteristics of the AgI-NH_4I system and that of the AgI-NaI system reinforces the conclusion that the former system yields the more active aerosol for cloud seeding purposes.

INTRODUCTION

A number of investigators have attempted to measure the size of particles obtained from various acetone solution generators by means of electron microscopy (Steele and Krebs, 1966; de Pena and Caimi, 1967; and Mossop and Tuck-Lee, 1968). In previous reports (Petersen and Davis, 1970 and 1971) the analysis of silver iodide particles obtained from combustion of AgI-NaI-acetone solutions was accomplished by means of the well-known x-ray diffraction Fourier analysis involving the deconvolution of broadened and standard diffraction profiles for the sample. Further advances in this technique have been presented by Johnson and Davis (1972).

The electron microscope methods suffer from the disadvantage of poor statistics of counting because of the limited number of particles that can be observed on the electron microscope grid and the possibility of overlapping. It also suffers from the disadvantage of the lack of compositional analysis such that impurities might be counted (unless some physically identifiable aspect can be observed). The most obvious drawback of this technique is the limited number of particles that constitute the sample, thus precluding the obtaining of a high degree of reliability in the results. In the x-ray diffraction technique as described by Petersen and Davis a large number of particles (above $10^{10} cm^{-2}$ of sample surface) may be analyzed, the result representing an averaging over a considerable volume of the aerosol sample.

Another aspect of this work which requires further understanding is the relationship between actual particle size and crystallite size. In the discussion by Petersen and Davis (1971, page 285) the distinction is made between individual particles in the AgI and NaI aggregate and shell-core composite particles. Of more importance in our present work is the distinction made by Johnson and Davis (1972) between the crystallite size and the aggregate particle size, the latter being the probable active nucleus for ice formation in aerosols which have not been properly diluted. In order to properly investigate the aggregate particle size one must resort to either the electron microscope or the low angle scattering technique which has been recently developed (see, for example, papers by Guinier and Fournet, 1955, and Beaman et al., 1957). Addition of this capability will be reality in our laboratory within the next few months. The results obtained by Petersen and Davis, and Johnson and Davis, however, all indicate that the crystallite size in properly diluted aerosol samples would be equal to the particle size because of the correspondence of their results with those of Mossop and Tuck-Lee (1968) from electron microscopy. There still remains considerable work to be carried out with the low angle scattering device for a complete understanding of the problem.

In the previous studies the analysis of the AgI and NaI aerosols was complicated by the presence of the sodium iodide component whose x-ray diffraction spectrum often coincided or overlapped with the spectrum of AgI.

In the present study we describe the particle size and size distribution of AgI components of the aerosols obtained by combustion of AgI-NH_4I-acetone solutions. The ammonium iodide component is destroyed in the combustion process and although a trace amount of the ammonia probably remains on the aerosol (M. L. Corrin, personal communication) the bulk of the material has been removed, leaving the silver iodide relatively uncontaminated, so that the diffraction peaks can be measured without difficulty. It was also discovered, however, that under certain conditions of combustion the ammonium iodide system results in aerosols containing considerable proportion of 21H AgI polytype (Davis and Petersen, 1970). Only samples having an insignificant proportion of this polytype will result in a reliable particle size analysis.

LOW OUTPUT NWC GENERATOR

Description: The AgI generator was developed at the Naval Weapons Center, China Lake, California. It consists of an ultrasonic nebulizer operating in a container filled with an acetone solution. The nebulizer produces a cloud of very uniformly sized droplets. The droplets are exhausted from the container past a baffle system that eliminates bigger drops and the resulting aerosol is burned. The device is described in Koff and St.-Amand (1971).

Modifications to the Generator: A few minor modifications that have been made on the device are:

(1) Addition of a provision to feed acetone vapor to the blower to decrease evaporation of the acetone droplets before burning and to control the stoichiometry.

(2) Substitution of a stainless steel screen for a ceramic grid on top of the burner. This permits the burner to operate for longer times between cleanouts necessitated by AgI deposits on the grid, and also gives an increase in rate of acetone combustion.

Method of Operation: Two modes of operation are possible when using this generator. The cool flame mode, illustrated in Figure 1-A, is achieved by using a power setting of 8 to 10 on the generator. The flame burns above the burner shield and has a temperature of 925 ± 50C with fuel flow of about 10 $cm^3 min^{-1}$.

The second, or "blowtorch," mode is achieved by setting the power control at about 4 or 5. Then the flame burns down inside the burner shield (Figure 1-B) and makes a slight roar like a blowtorch. The flame temperature is 1125 ± 50C with a fuel flow of about 3 1/2 $cm^3 min^{-1}$. Mean droplet diameter with a power setting of 10 was 5.9 μ, and with a power setting of 5 was 5.1 μ. These measurements were made by replicating the droplets on Formvar-coated slides and counting by phase-contrast microscopy. All runs for particle size determination were carried out using an acetone solution of 4% AgI by weight with a 2:1 mole ratio AgI:NH_4I.

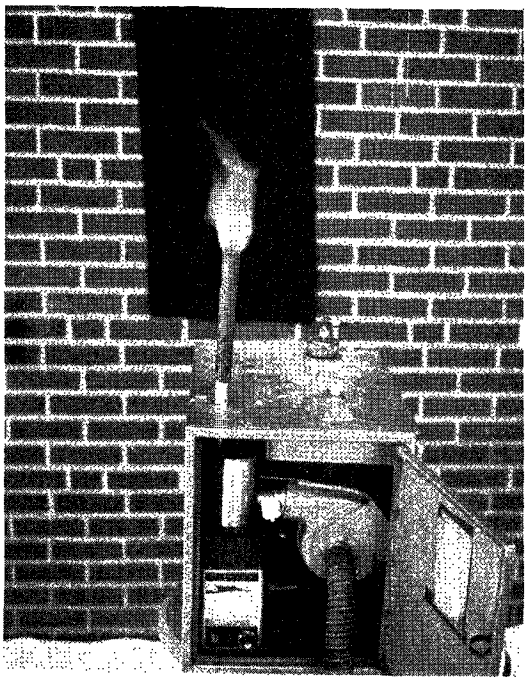


Figure 1-A. Cool flame mode.

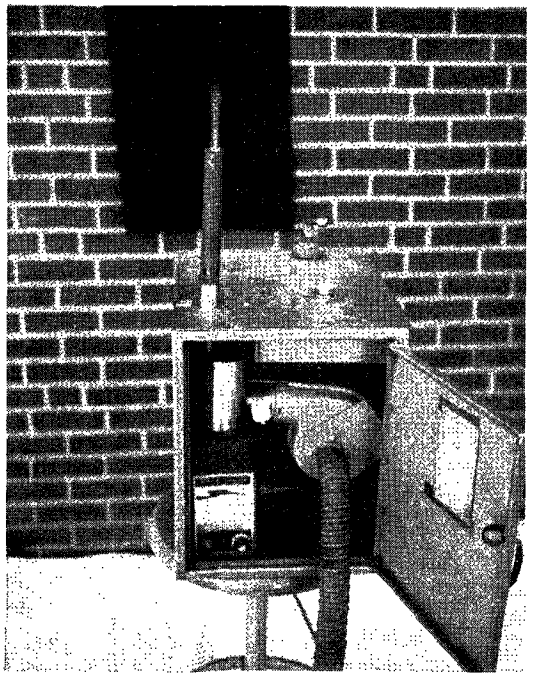


Figure 1-B. Hot flame mode.

Figure 1.

Low output silver iodide generator designed by the Naval Weapons Center, China Lake, Ca. Front view showing lower piezoelectric system and stack.

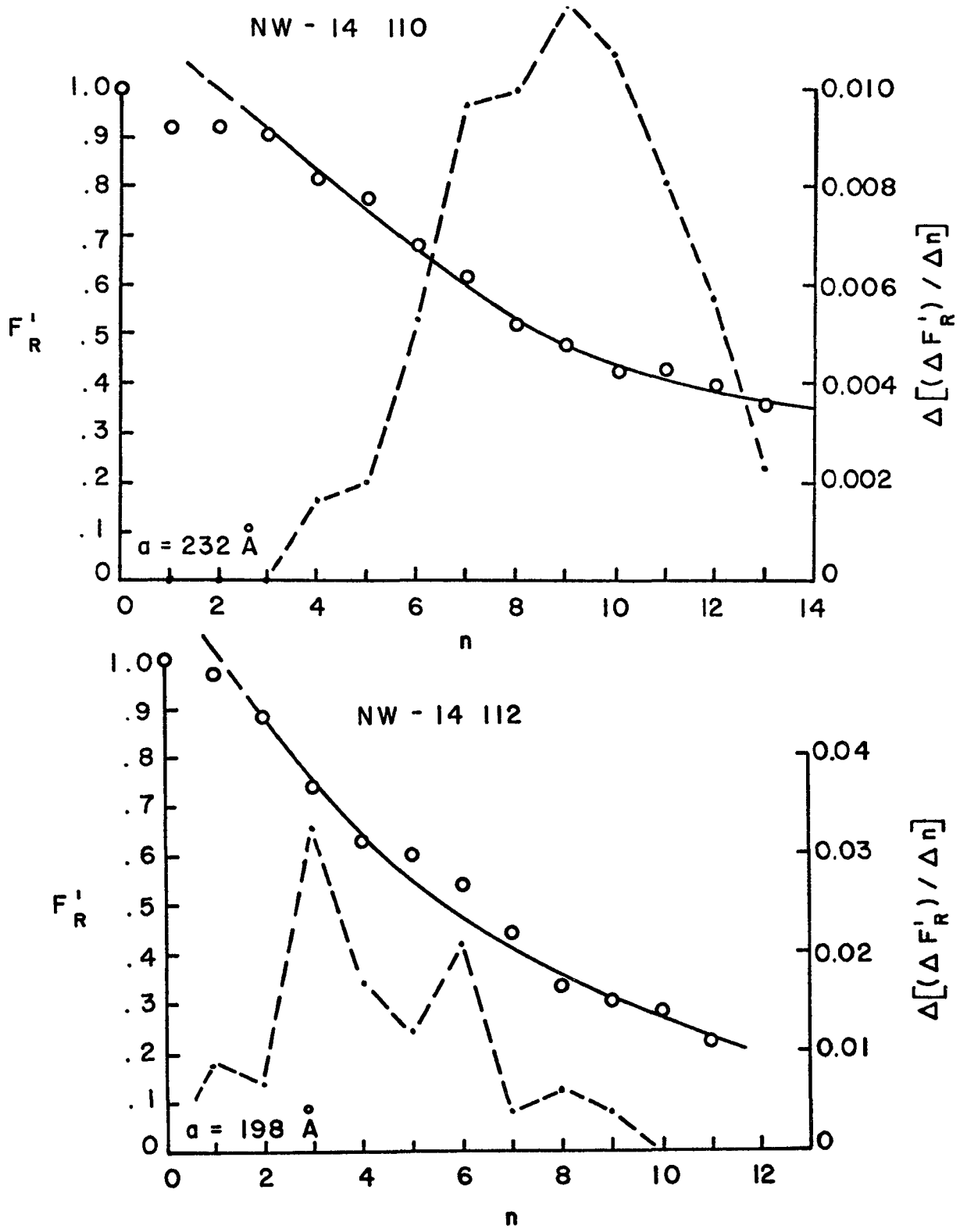


Figure 2. Plot of normalized Fourier coefficients vs. coefficient order n and resulting second difference plot. NW-14.

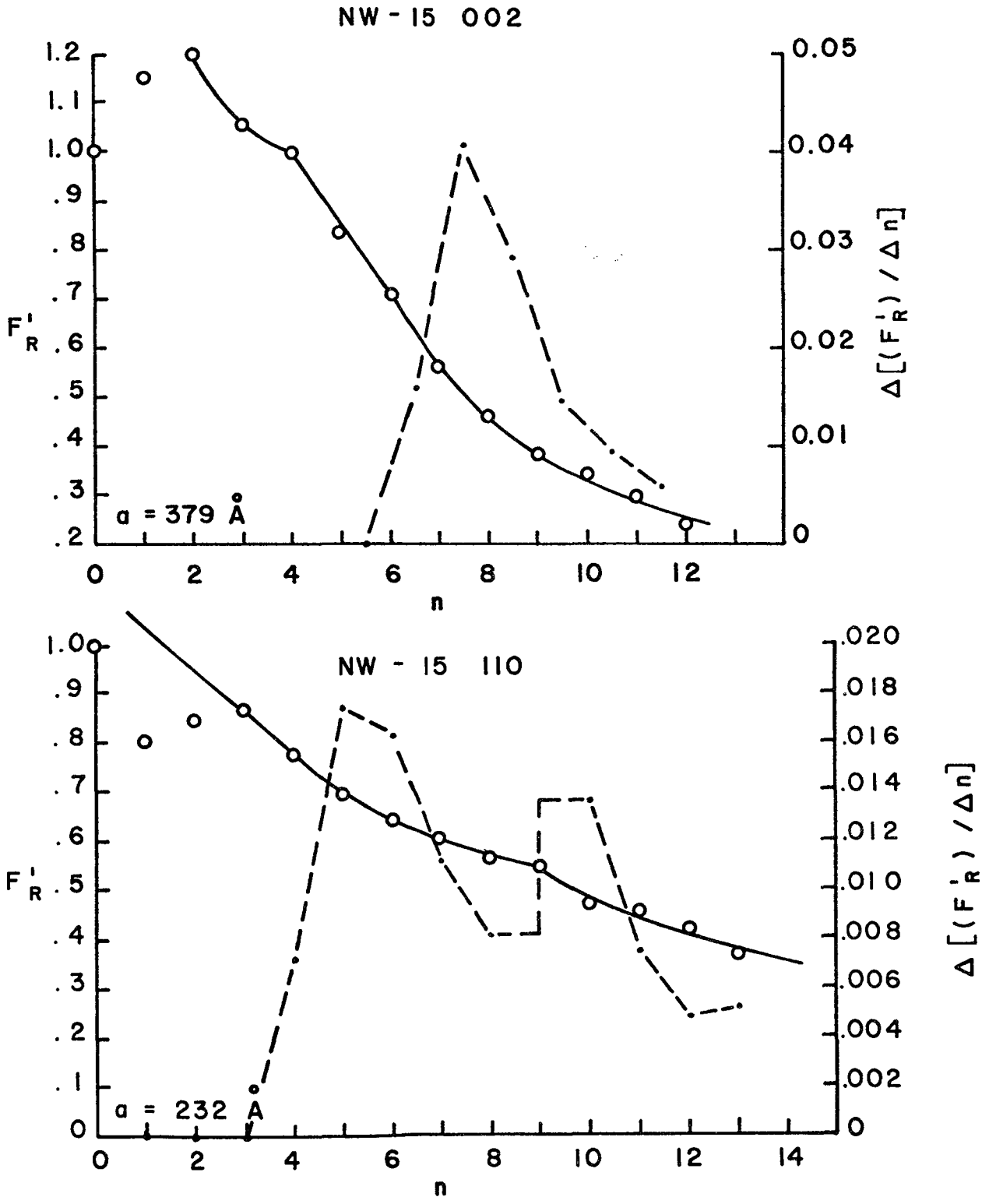
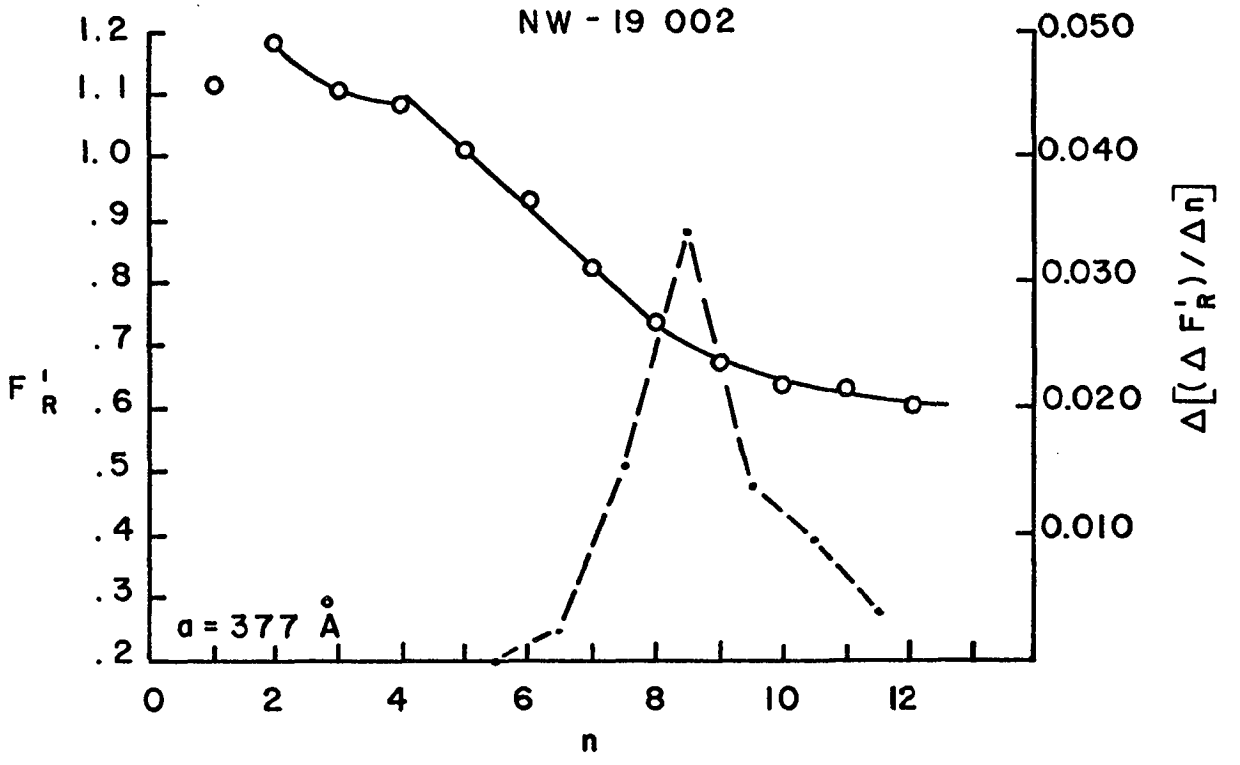


Figure 3. Plot of normalized Fourier coefficients vs. coefficient order n and resulting second difference plot. NW-15.



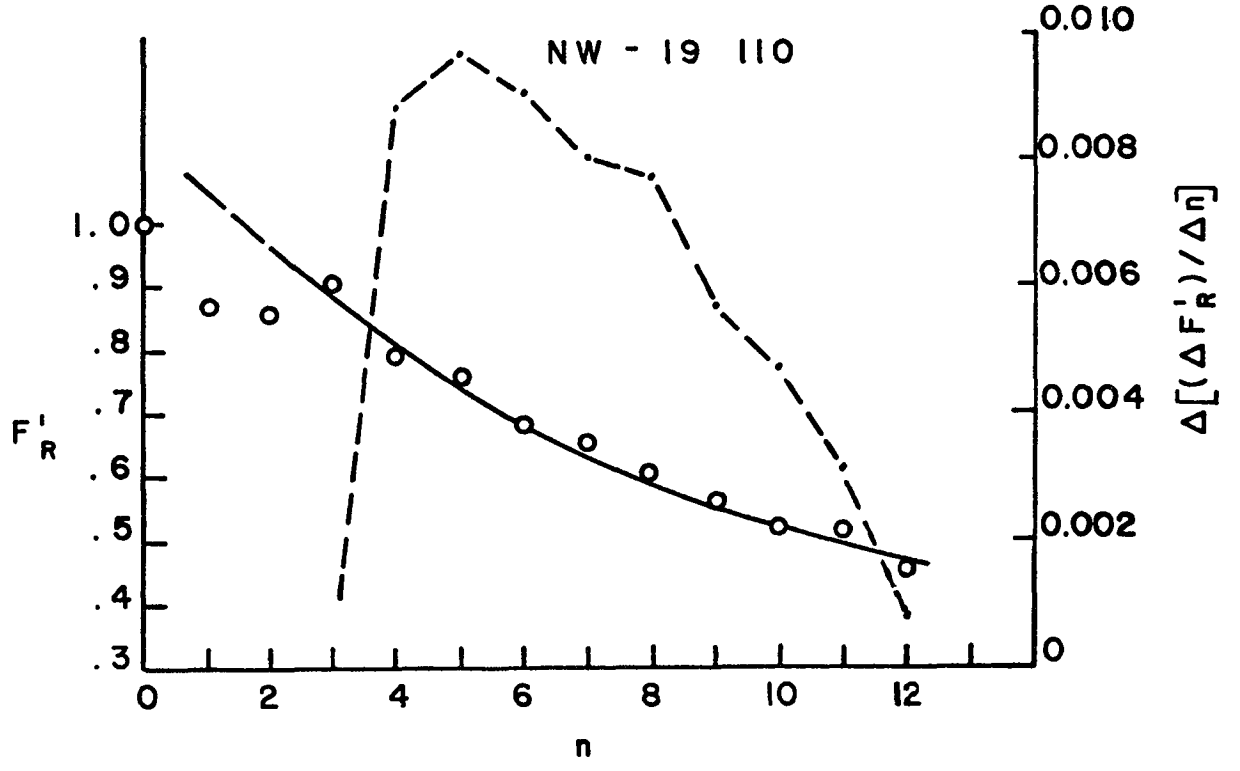


Figure 4. Plot of normalized Fourier coefficients vs. coefficient order n and resulting second differnce plot. NW-19.

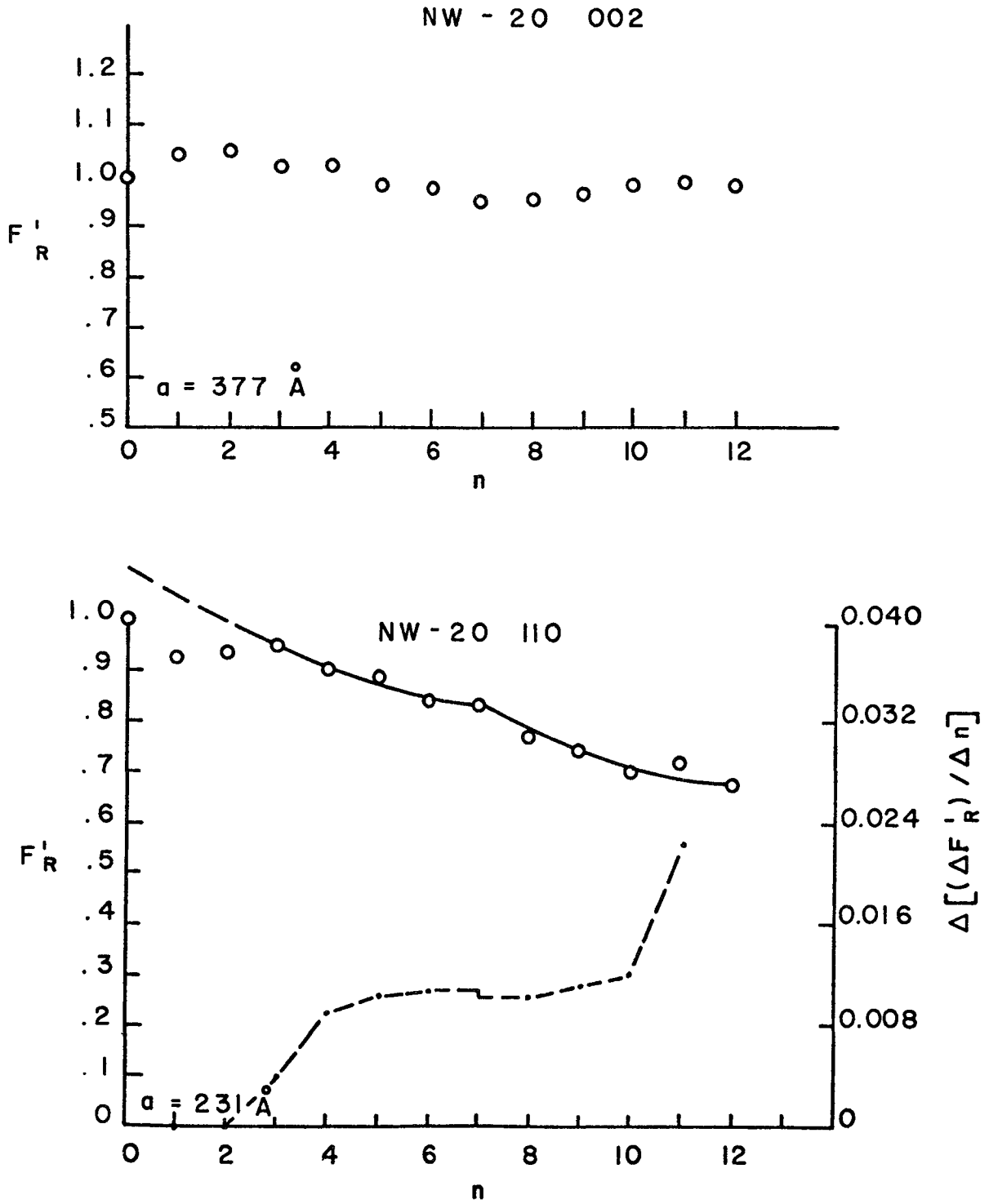


Figure 5. Plot of normalized Fourier coefficients vs. coefficient order n and resulting second difference plot. NW-20.

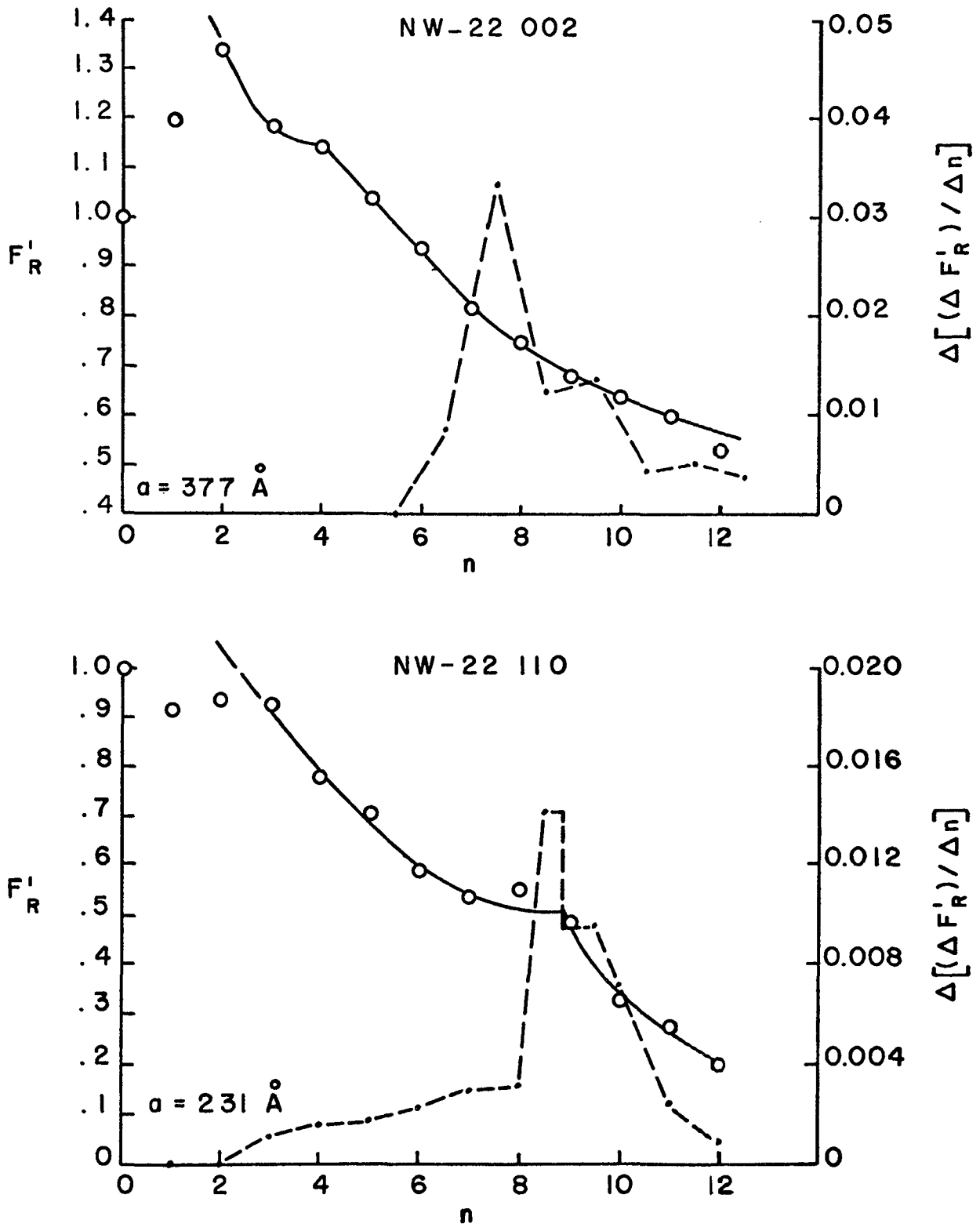


Figure 6. Plot of normalized Fourier coefficients vs. coefficient order n and resulting second difference plot. NW-22.

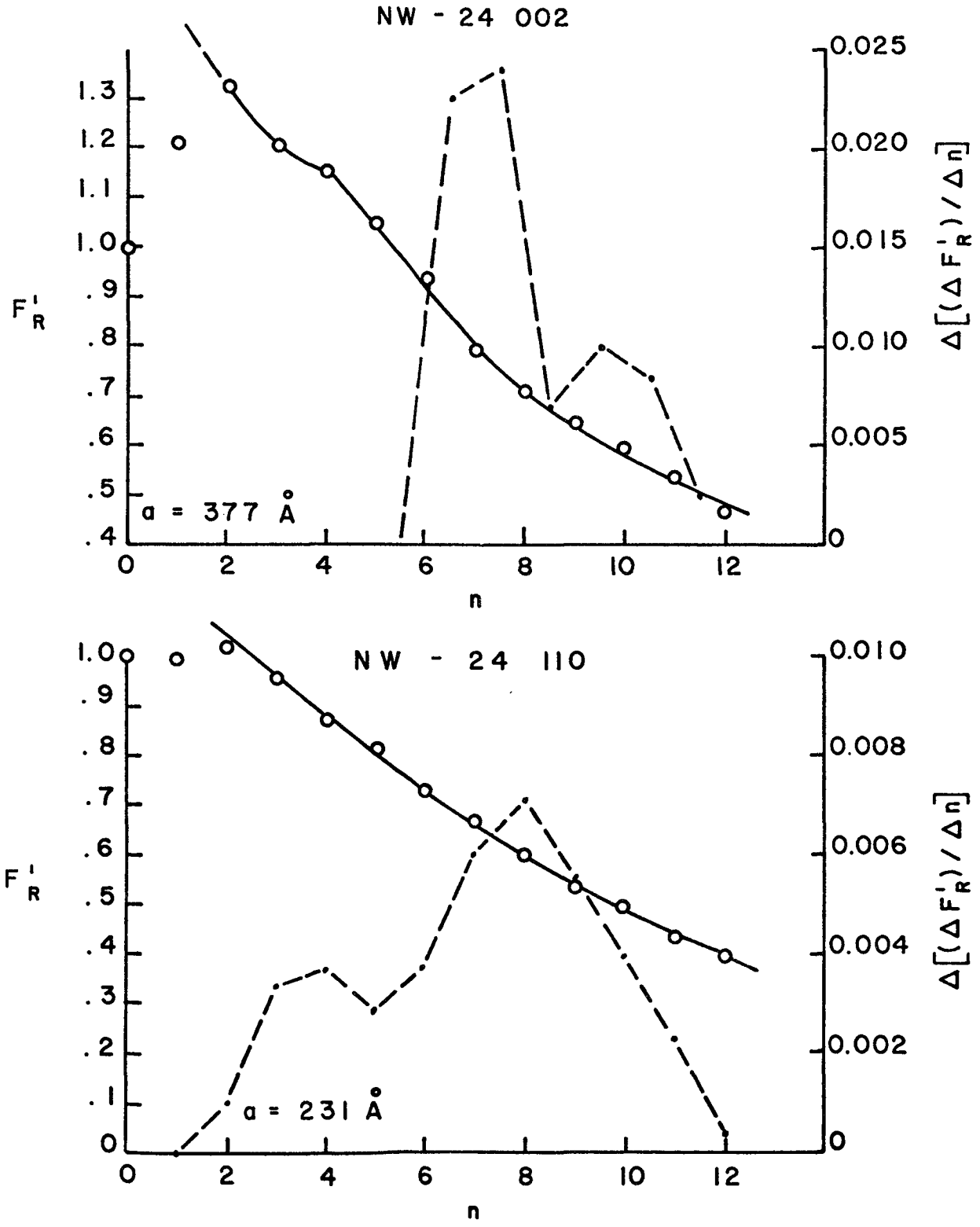


Figure 7. Plot of normalized Fourier coefficients vs. coefficient order n and resulting second difference plot. NW-24.

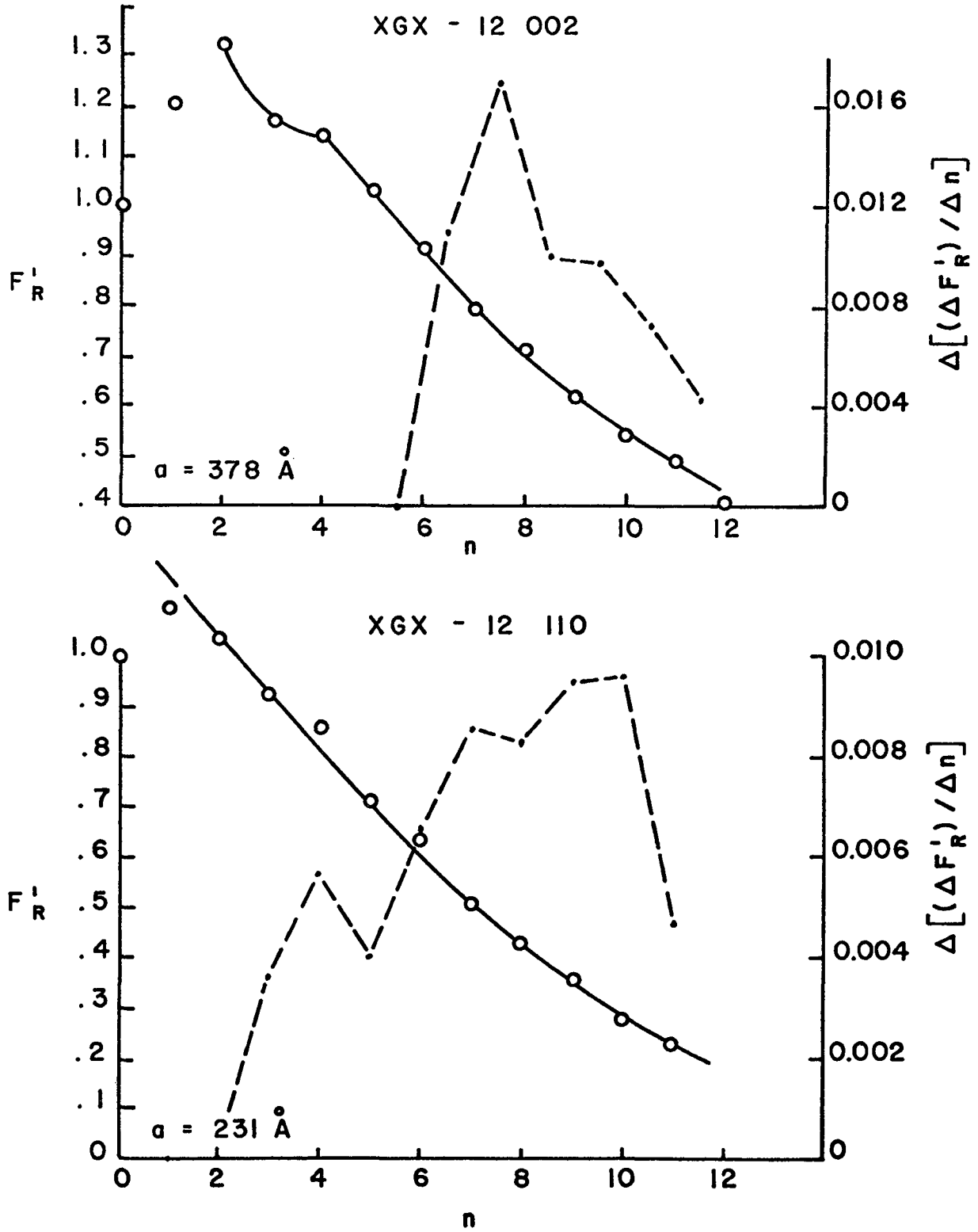


Figure 8. Plot of normalized Fourier coefficients vs. coefficient order n and resulting second difference plot. XGX-12.

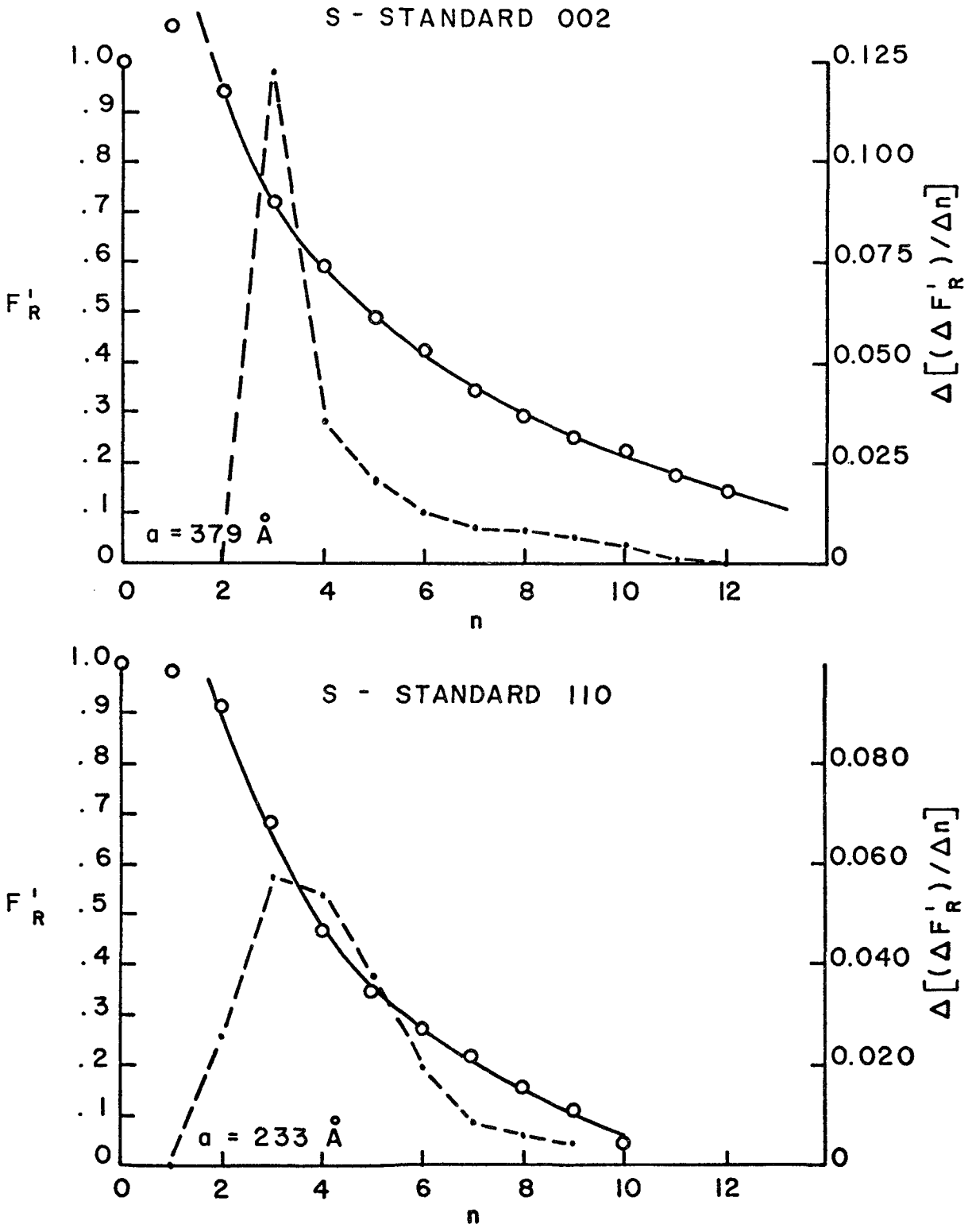


Figure 9. Plot of normalized Fourier coefficients versus coefficient order n and resulting second difference plot. S-STD.

Fuel flow rate through the burner cannot be accurately determined but an approximate figure has been calculated for each power setting of the generator. This was done by calibrating the flow for each needle valve setting and noting whether or not the solution level in the nebulizer chamber would rise or fall for a known period of operation. These flow rates were used in calculations for nucleation efficiencies.

RESULTS

Mean Particle Size Estimates

All samples of the aerosols were collected on filter paper and analyzed in a standard x-ray diffractometer. Computer analysis then resulted in the determination of variance-range parameters, estimates of apparent particle size (see Wilson, 1955, for definitions), the Fourier deconvolution estimation of apparent particle size, and the Williamson-Hall determination of mean particle size corrected for root-mean square strain, and an estimate of the particle size distribution of the aerosols obtained from the plot of the second derivative (difference approximation) of Fourier coefficients versus order of the coefficient. Further details of the technique have been described by Johnson, et al.(1972).

In this report we describe the results for eight samples, six obtained from the low output Naval Weapons Center generator, one from the I.A.S. laboratory low output generator, and one from a standard sample in which a maximum amount of strain was introduced by grinding in a mortar and pestle, hereafter referred to as S-standard. The plot of strain-corrected, normalized Fourier coefficients F'_R versus coefficient order n and a resulting second derivative (difference) plot for the basal (002) and prismatic (110) reflections of all samples are presented in Figures 2 through 9 and the summary of particle size information presented in Tables 1 through 3. In the case of Figures 2 through 9 another estimate of the mean apparent size (diameter) ε_a can be obtained by using the estimated median from the distributions of Figures 2 - 9. Also in Table 2, ε_k is the apparent size parameter obtained from the variance-range function, and ε_a is the apparent size estimation obtained from the Fourier deconvolution. For ε_a the value of n is multiplied by the "cell" length a (Warren, 1955, p. 485) to obtain "column" length. D_W is the Williamson-Hall size parameter obtained by a plot of $\beta\cos\theta/\lambda$ versus 1/d. Plots of the six samples are given in Figures 10 and 11.

One of the obvious features of the apparent particle size estimations is a decrease of size with increasing 2θ and increasing $h^2 + k^2 + \ell^2$ (Table 2), which results from the strain effect on the broadening and is not accounted for in either apparent size estimations ε_k or ε_F. This is expected and it is known from the characteristics of the diffraction versus Bragg angle (2θ) that the low angle peaks (e.g., 002) give a more accurate estimation of particle size, and the high angle peaks (e.g., 220) give a better estimation of the strain stored in the sample.

In examination of Table 2 one will note that the values for ε_a are generally larger than those of ε_k or ε_F. This is an expected result inasmuch

as ε_a is a strain-insensitive apparent size estimate. The larger value for this estimate comes from the removal of the broadening contribution for stored strain energy in the aerosol. However, the values for ε_a are subject to some uncertainty themselves because of the sensitivity of $^{a}\Delta[(\Delta F'_R)\Delta\eta]$ to the curvefitting of the F'_R versus n data, and because of the slight uncertainty in estimating where the "hook" effect begins. It is also interesting to note that there is in general better agreement between ε_k and ε_a which would lead one to conclude that the ε_k estimate (from the variance-range technique) is less strain sensitive than the Fourier estimate.

Table 1.

SUMMARY OF SIZE-STRAIN PARAMETERS

NW	T_f °C	D_W μ	ξ	%C	R(β*, d*)	η	color, unif.
20	915	.124	.0005	26	0.71	2.5	dk grn to blk; fair
14	925	.095	.0012	82	0.85	4.5	yel & red, spotted; poor
22	926	.169	.0020	59	0.96	6.0	lt yel; exc.
19	955	.137	.0012	92	0.89	2.0	lt yel; exc.
15	970	.114	.0010	80	0.79	6.0	lt yel; exc.
24	1100	.088	.0004	74	0.64	6.0	lt yel; good
S-STD	23°	.096	.0032	95	0.84	--	---
XGX-12	≈850°	.094	.0006	82	0.76	7.0	yel-brwn; good

η = direct beam transmission relative to blank, percent

ξ = root-mean-square strain stored in sample

R = simple correlation coefficient of Williamson-Hall plots

%C = percent cubic phase

D_W = Fourier size estimate from Williamson-Hall plots

T_f = flame temperature in generator combustion chamber, $\pm$ 50°C

color, unif = aerosol color and texture uniformity as collected in filter

Table 2.

APPARENT PARTICLE DIAMETER ESTIMATIONS (in Angstroms)

	002	110	112	300	220	
NW-14						
ε_k	--	662	535	442	262	
ε_F	--	695	735	510	560	D_w = 1140
ε_a	--	2090	790	--	--	
NW-15						
ε_k	885	644	640	340	285	
ε_F	704	678	755	488	550	D_w = 947
ε_a	3040	1855	--	--	--	
NW-19						
ε_k	2144	819	1490	370	383	
ε_F	919	732	890	557	578	D_w = 1365
ε_a	3230	1625	--	--	--	
NW-20						
ε_k	4726	2087	1549	1311	412	
ε_F	1134	883	1031	754	891	D_w = 1243
ε_a	--	>2310	--	--	--	
NW-22						
ε_k	1737	709	555	366	262	
ε_F	885	669	671	431	457	D_w = 1694
ε_a	3230	2040	--	--	--	
NW-24						
ε_k	1713	933	578	642	363	
ε_F	843	731	748	617	741	D_w = 878
ε_a	3020	1625	--	--	--	
XGX-12						
ε_k	1659	756	765	480	374	
ε_F	829	717	763	562	647	D_w = 945
ε_a	3230	1740	--	--	--	
S-STD						
ε_k	474	295	198	147	135	
ε_F	566	427	370	236	311	D_w = 988
ε_a	1710	929	--	--	--	

Table 3.

COEFFICIENT OF VARIANCE FOR SELECTED SAMPLES

Sample	Type	$\overline{\varepsilon}\,\mu$	$\sigma\,\mu$	$\sigma/\overline{\varepsilon}$
NW-15 (002)	NH_4I-acetone	0.311	0.049	0.159
NW-15 (110)	NH_4I-acetone	0.178	0.053	0.298
NW-19 (002)	NH_4I-acetone	0.332	0.044	0.131
NW-19 (110)	NH_4I-acetone	0.152	0.054	0.352
Smith-Heffernan	NaI-kerosene	0.0073	0.0029	0.397
de Pena - Caimi	KI-acetone	0.0304	0.0205	0.675
Mossop-Tuck-Lee	NaI-acetone	0.0850	0.0326	0.384

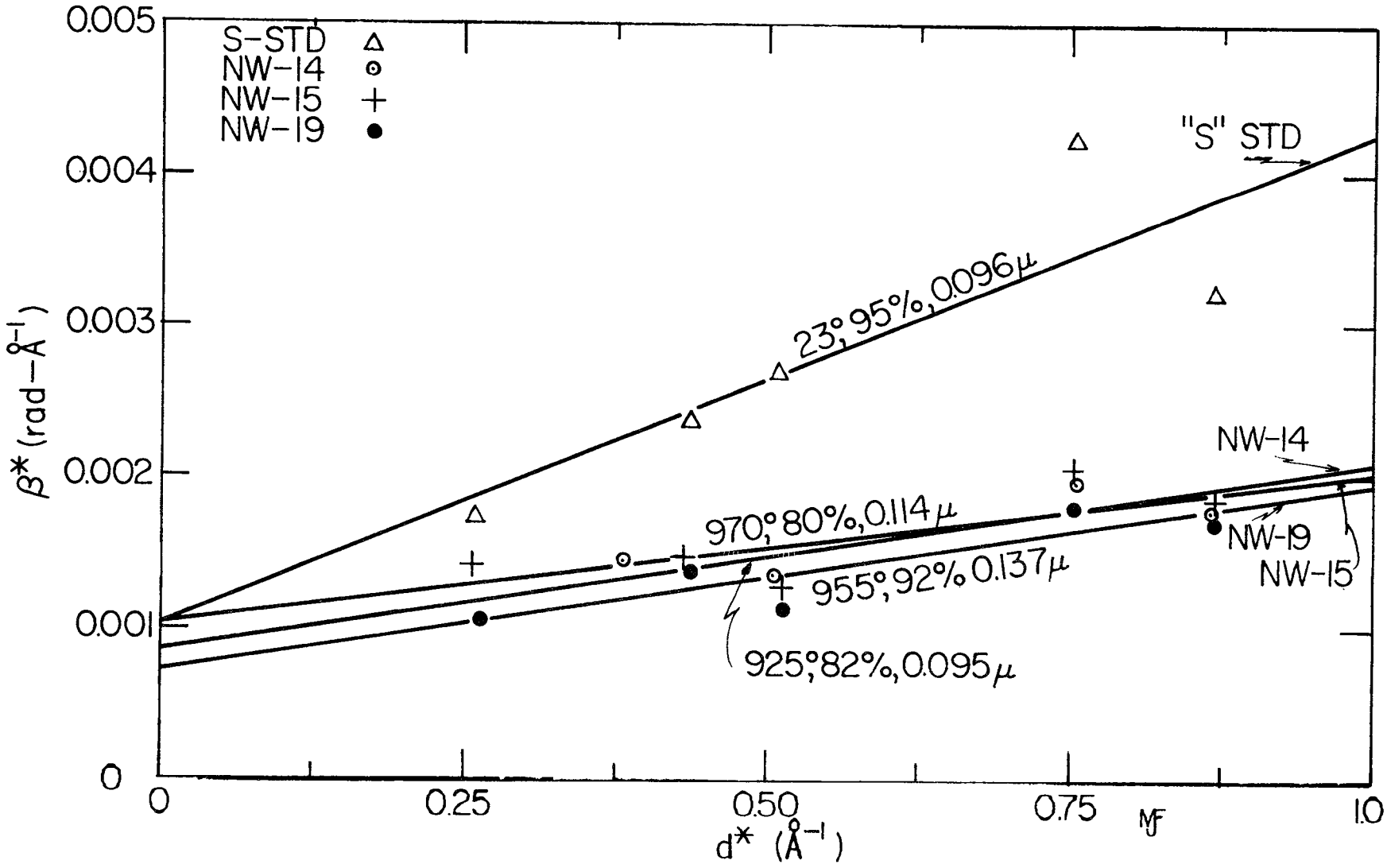


Figure 10.

Williamson-Hall least squares regression for NW-14, 15, 19, and S-STD.

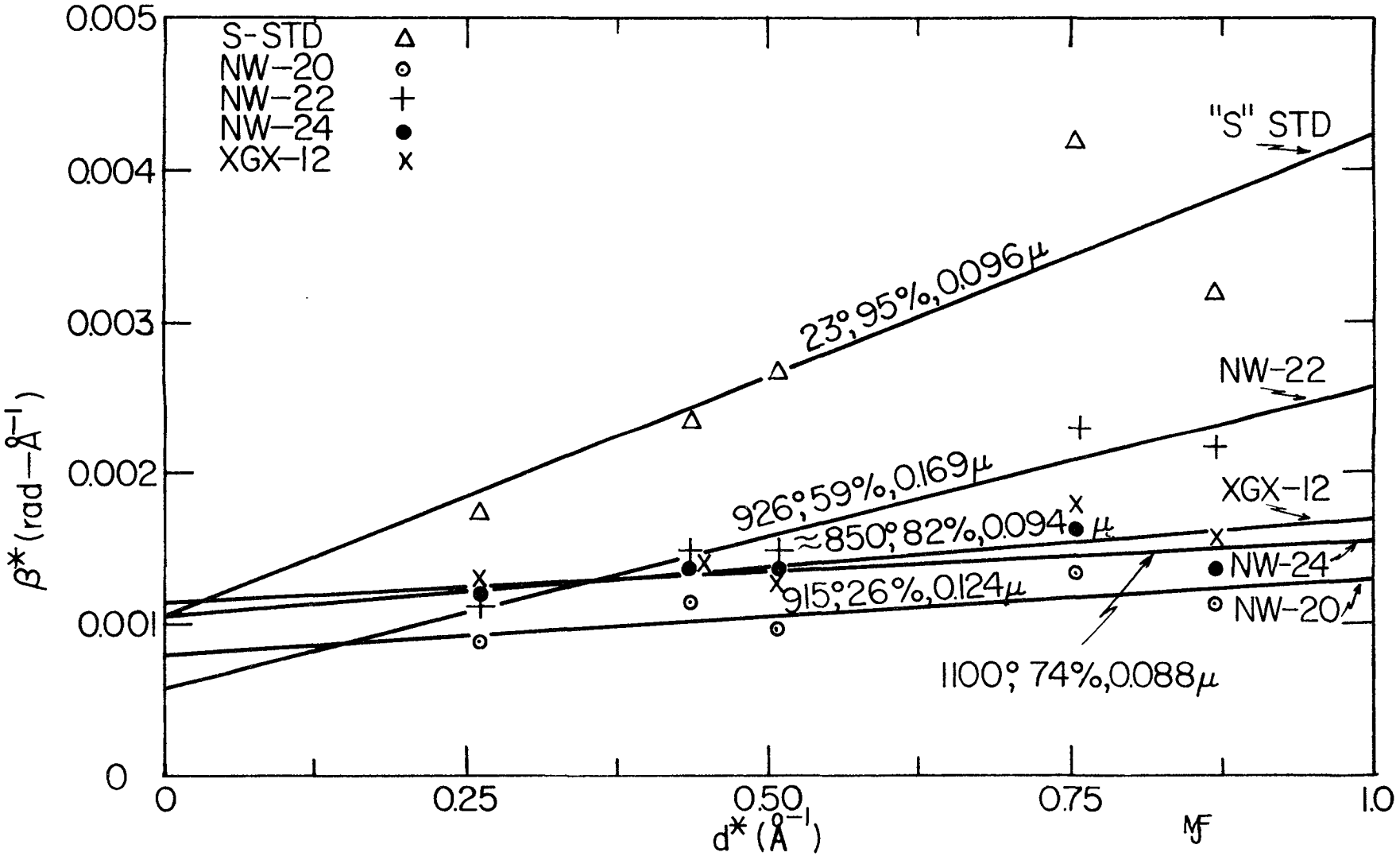


Figure 11.

Williamson-Hall least squares regression for samples NW-20, 22, 24 and S-STD.

In the case of NW-14 the 002 peak was not scanned because of the presence of polytype and other impurities which distorted the profile. The 112 reflection was analyzed for the same information that would ordinarily be given by the 002. However, it should be understood that the 112 does not give an apparent diameter equal to that of the 002, but because of the crystallographic position will represent an intermediate between the basal and the prismatic diameters.

The Williamson-Hall size estimate, D_W, is obtained in a manner similar to ε_a, there being a strain correction. However, the value for D_W, being a result of a least squares regression to all hkℓ estimates, should be interpreted as a mean particle size estimate without regard to crystallographic orientation. Thus it is not an "apparent"size as are the values of ε.

The technique leading to the value of D_W is the most straightforward for elimination of strain, and gives the overall best estimate of average particle size of any of the techniques used. Correlation of the particle size with other parameters will therefore rely on the values of D_W in this and in future studies.

In examination of Table 1, some interesting aspects are noted. The table is arranged in order of increasing flame temperature as measured by a thermocouple placed in the hot tipportion of the flame. There appears to be no correlation between flame temperature and mean particle size or strain. There also seems to be a variable amount of the cubic (3C) phase which also shows no correlation with flame temperature.

It is also of interest to compare the present results with those of Petersen and Davis (1970, 1971) for the NaI-bearing aerosol. The values for flame temperature of this generator and that used by Petersen and Davis are of the same order of magnitude but we observe that the particle sizes obtained in the present study are somewhat greater than that obtained by Petersen and Davis. We observed in the latter study particle sizes (D_W) ranging from 0.05 to 0.13 μ diameter with a composite average of 0.085 μ, whereas in the present study the D_W range is from 0.09 to 0.17 with a composite average of 0.121 μ. Even though both sets of results are similar, it might be significant that the ammonium iodide-bearing system yields particles of a somewhat larger size and also the greater nucleation efficiencies at higher temperatures as observed in cloud chamber studies. The chamber studies in our laboratory indicate that the greatest efficiencies at the higher temperatures are obtained from high AgI concentrations (on the order of 10% or greater) which might reflect a larger aerosol particle resulting from high vapor density of AgI and subsequent condensation into larger aerosol particles. Time limitations in the present study have not allowed an exhaustive analysis of the concentration versus particle size relationship.

Particle Size Distributions

Figure 12 demonstrates some of the irregularities observed in certain of the second-difference plots of these samples. In this figure we show the data from HKℓ = 300 of XGX-12 and the S-STD. The appearance of these features is especially noticeable in all 300 data and, along with other

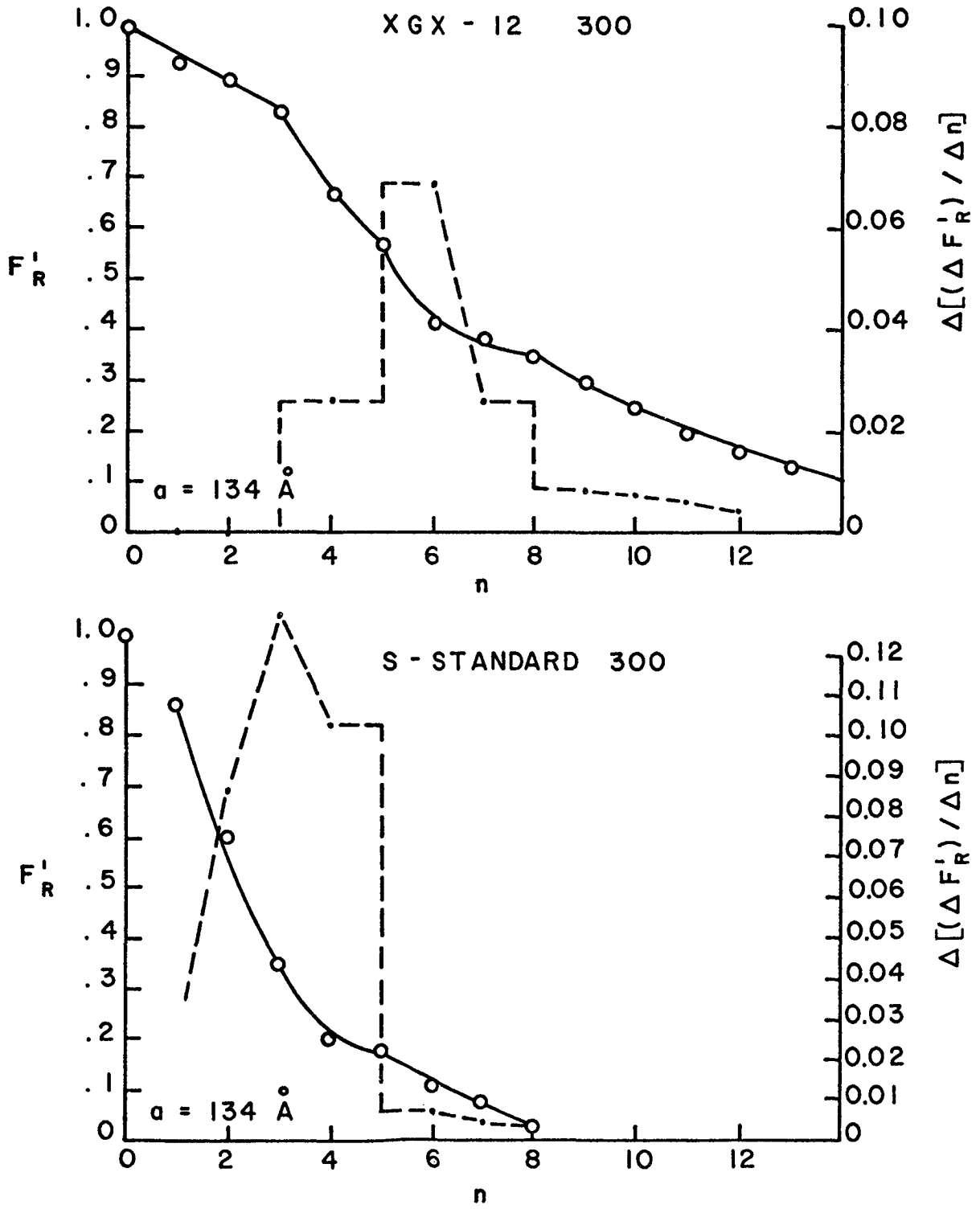


Figure 12. Plot of normalized Fourier coefficients vs. coefficient order n and resulting second difference plot. 300 peak of XGX-12 and S-STD.

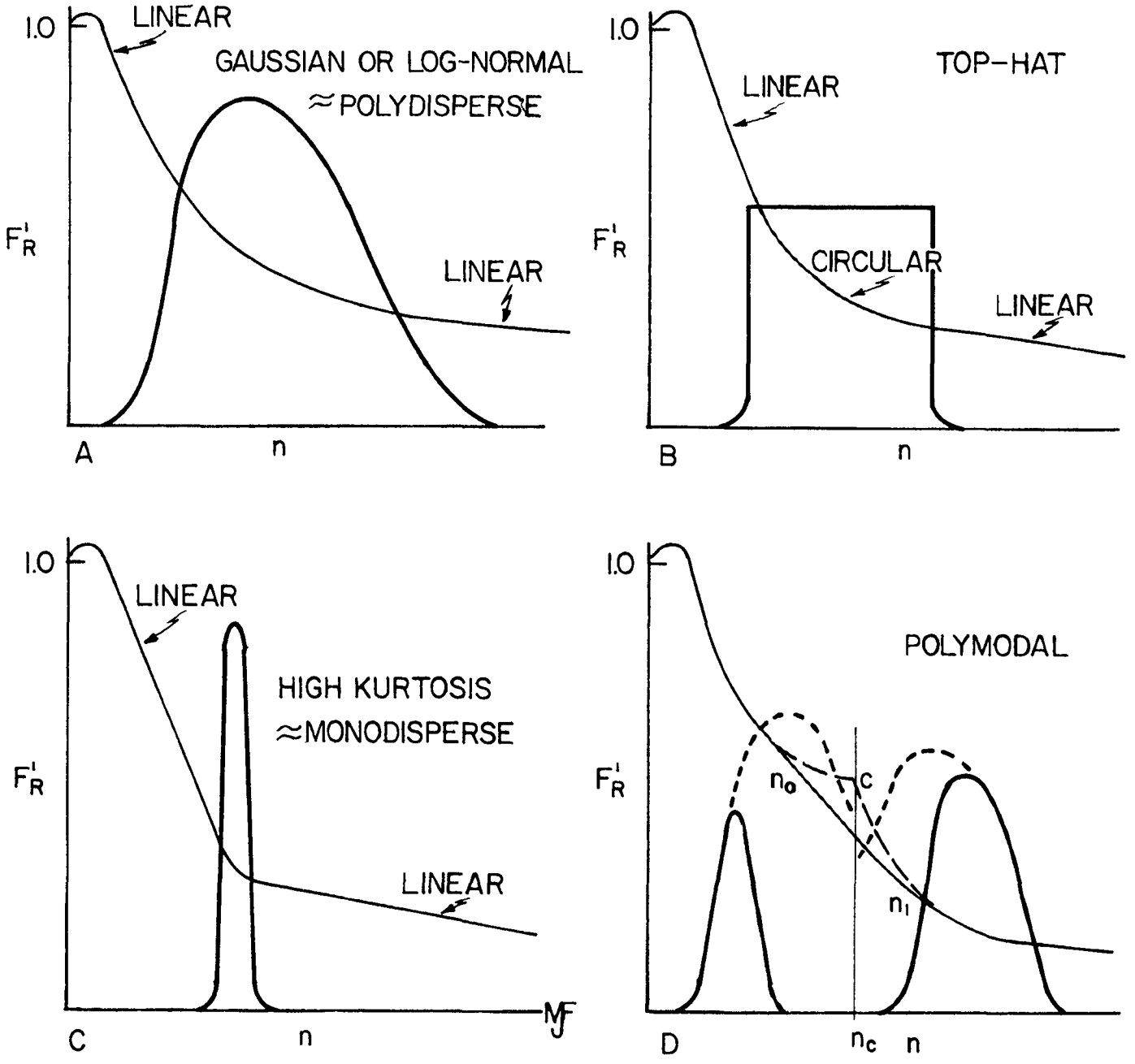


Figure 13. Examples of four types of particle size distributions obtained from Fourier coefficient vs. order second difference plots.

subtle features of these profiles, leads us to view them with caution. They also occur, but less pronounced, in many of the other profiles.

The cuspate features, such as observed in Figure 12, result in defined values for the second derivative at that value of n. Figure 13 illustrates a number of hypothetical possibilities for the shape of this plot and the type of distribution expected for the aerosol. In A of the figure we observe the normal F'_R versus n trend resulting in either Gaussian or log-normal (or some hybrid) distribution of polydispersed particles. Note that we have included the so-called "hook effect" region near 1.0 which is observed in nearly all of our analyses. In B of Figure 13 we observe a "top-hat" distribution such as would be obtained from two linear regions on either side of a circular flexation. This is similar to C in which we have two linear regions separated by the region of curvature which may or may not be circular, but results in a distribution of high kurtosis such as would be expected for a nearly monodispersed aerosol. In D we observe two type of polymodel distributions. In this case, simplified to bimodel, regions of significant curvature are separated by linear regions (between N_0 and N_1) such that the second derivative (difference) results in two discrete maxima. A more complex case would be obtained when either some curvature exists between N_0 and N_1 or an actual discontinuity in curvature such as indicated at C. In this case we would have a region of finite particle sizes existing between the two modes of the distribution.

Now in the case of our experimental data, we have not attempted to examine the shapes of each curve in great detail but have attempted to smooth the trend but not ignore obvious cusps or other discontinuities. The strain correction, moreover, insignificantly changes the cuspate features in all diagrams. In our experience with development of the methods of Fourier analysis and from the literature dealing with the second derivative plots, we are prone to attribute many of the minor variations in the trends to experimental errors or errors in measurement of the profiles which will result in subsequent irregularities of the Fourier coeffiecient trends. We hesitate at this time to ascribe any significance to the detailed structure developed in any of the second derivative plots. However, the plots do serve to indicate the magnitude of monodisperse or polydisperse character of the aerosols.

The kurtosis of the distributions also represents a measure of the polydisperse nature of the aerosol, and is best indicated by the coefficient of variance, $\sigma/\bar{\varepsilon}$. The value of $\bar{\varepsilon}$ is obtained by averaging the grouped data of the second difference plot. Thus $\bar{\varepsilon}$ should be nearly equal to ε_a. The values for $\sigma/\bar{\varepsilon}$ for NW-15 and NW-19 (002 and 110) are compared with the similar parameters obtained from the Smith-Heffernan, de Pena-Caimi, and Mossop-Tuck-Lee aerosols in Table 3. Except for NW-19 (110) and other $\sigma/\bar{\varepsilon}$ values are significantly less than those given by the three aerosols quoted from the literature. This would indicate that the aerosol produced by the low output NWC generator is measurably more monodisperse than those aerosols produced by standard seeding generators but that there is still a finite and significant spread to the particle sizes. Thus, it would be incorrect to label this generator a "monodisperse" generator. However, these data show a significantly narrower distribution to the sizes as compared to other field type generators. Further discussion of this point will be raised in a later section.

Shape and Strain Information

Because the aerosol is a mixture of both cubic and hexagonal phases, it is not too meaningful to attempt to construct an accurate shape model for the silver iodide particle from the apparent size data although under ideal conditions one can use various models to go from apparent to true particle sizes to ascertain the shape of the particle. In this particular series of experiments since both cubic and hexagonal phases are intimately mixed no such model can be reliably given. The ε_a data of Table 2 suggest a gross short prismatic form ($c/a \approx 3$) for the crystallites.

Also of interest is a comparison of the stored anelastic strain values, (ξ), for the present experiments in comparison with those of Petersen and Davis (1971). The values of storage strain are of the same order of magnitude except for NW-22 for which it is about twice as much strain as the mean value.

The S-standard analysis (Figure 9) was used to allow comparison of the stored strain in the aerosols with that obtained by grinding in a mortar and pestle which would seem to yield the highest possible stored strain (see Davis and Blair, 1969). The sample showing the next greatest amount of strain is NW-22; the value stored (0.22%) is considerably less than that of the S-standard where only 0.32% root-mean-square strain has been introduced. Although it was originally anticipated that the more highly strained samples would show the higher proportion of cubic AgI (as is well known to be the case in the grinding mechanism) we see no such obvious relationship from the data in Table 1 and we have not considered it worthwhile to further analyze the data. It thus appears that some chemical parameter may be as important as the mechanical effect of strain in changing the phase present in the aerosol. It is important to note that Ono and Kimura (1967) have observed a striking increase in the effectiveness of nucleation from the cubic (3C) phase, a phenomenon similarly noted by Davis and Blair (1969) in their study of deformed AgI, CuS, and Kaolinite.

There does appear to be a significant correlation (R=0.79) between the anelastic strain and the particle size (Figure 14). From this diagram it is observed that the smaller particles are capable of storing less strain than the larger particles. The explanation of this appears to lie in easy annealiability or solubility of the smaller particles in the presence of even relatively low humidities (<50%) and might be due to the residual ammonia contamination observed by Corrin in such aerosols. An interesting aspect of this plot is that the two samples (indicated by unfilled circles) whose values lie outside the rather good trend for the other data are ones which show anomalous colors in the bulk sample.

Cloud Chamber Results

In Figures 15 through 18 we present the results of the cloud chamber tests using the low output generator mounted in a wind tunnel and diluted with a 105 CFM blower. Details of the procedure and technique with this system are described in Donnan, et al., 1971. The analyses included limited data from 0.5% AgI and 10% AgI in NH_4I-acetone solutions and considerably

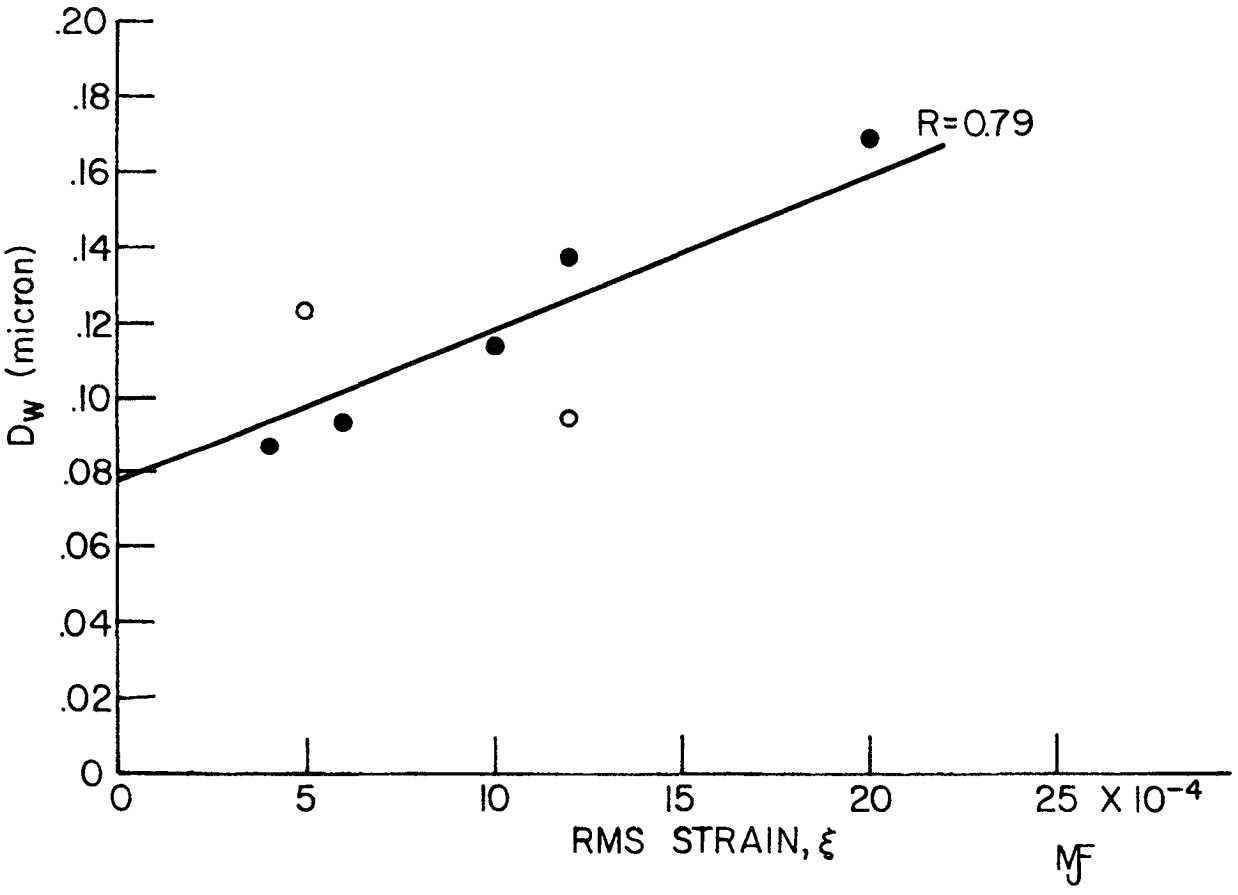


Figure 14.

Correlation of strain parameter ξ and particle size for NW series determinations.

more data from the 4% AgI solution. The individual data points were left unconnected to avoid biasing the opinions of the reader. A number of observations from these plots are summarized as follows:

1. The highest nucleation efficiencies in the -5 to -12°C region are obtained by using solutions of greatest AgI concentrations.

2. The tail-off in the vicinity of -15°C is most noticeable at the higher AgI concentrations.

3. Some of the data indicate possible anomalies in the region -10 to -15 (925°C data of Figure 15, runs 6, 7, and 8 in Figure 16).

4. Aerosols produced at the higher flame temperatures generally show higher nucleation efficiencies at temperatures of -10°C or lower (circles of Figure 15, runs 9, 10, 12, 13, and 24 of Figures 16 and 17, and circles of Figure 18).

A number of these features have been observed from other generators, i.e., the increase in nucleation efficiencies at the warmer temperatures for higher concentration solutions. The physical mechanism behind this observation is unclear but perhaps is related to the coagulation rate for high particle concentrations of AgI upon quenching. That the particles for the high concentration solutions are larger than the others is also consistent with the upward sweeping trend of the 0.5% AgI data which point to a greater dilution upon quenching and creation of a small particle population.

The tendency for the efficiency curves to bend over or "knee" in the moderately low temperature region (-10°C) is consistent with the nuclei size distribution data obtained in this study. If the generator yielded particles that were perfectly monodisperse (of unit size interval), there would be no nucleation above the activity threshold and 100% activation below this threshold, such that the activation curve would be a vertical line up to the maximum possible numbers obtainable (for a given particle size) and would bend over sharply to the horizontal at lower temperatures. Such is obviously not the case, but the trend at the knee is somewhat sharper than observed in most generators and does agree with the somewhat narrower distribution observed from the second difference plots presented above. We can thus conclude that this generator is a step better than others in producing particles of a monodisperse nature, but by no means are the particles uniformly of a single size.

The observation that the aerosol produced under higher flame temperature conditions yields higher efficiencies may be related to the rate of quenching and production of large particles. It might also be related to the breakup of AgI particles in each aerosol droplet. Figure 19 presents histograms of 200-droplet counts of the acetone solution droplets produced by the generator. The counts do not present a good statistical population but, if correct, indicate that the mode which yields the higher flame temperatures actually produces a larger mean droplet size, thus presenting a necessity of some type of multiparticle production from an individual droplet in the combustion process. There is no proof that the droplets retain an identity sufficient to yield particles before merging into the hot vapor of

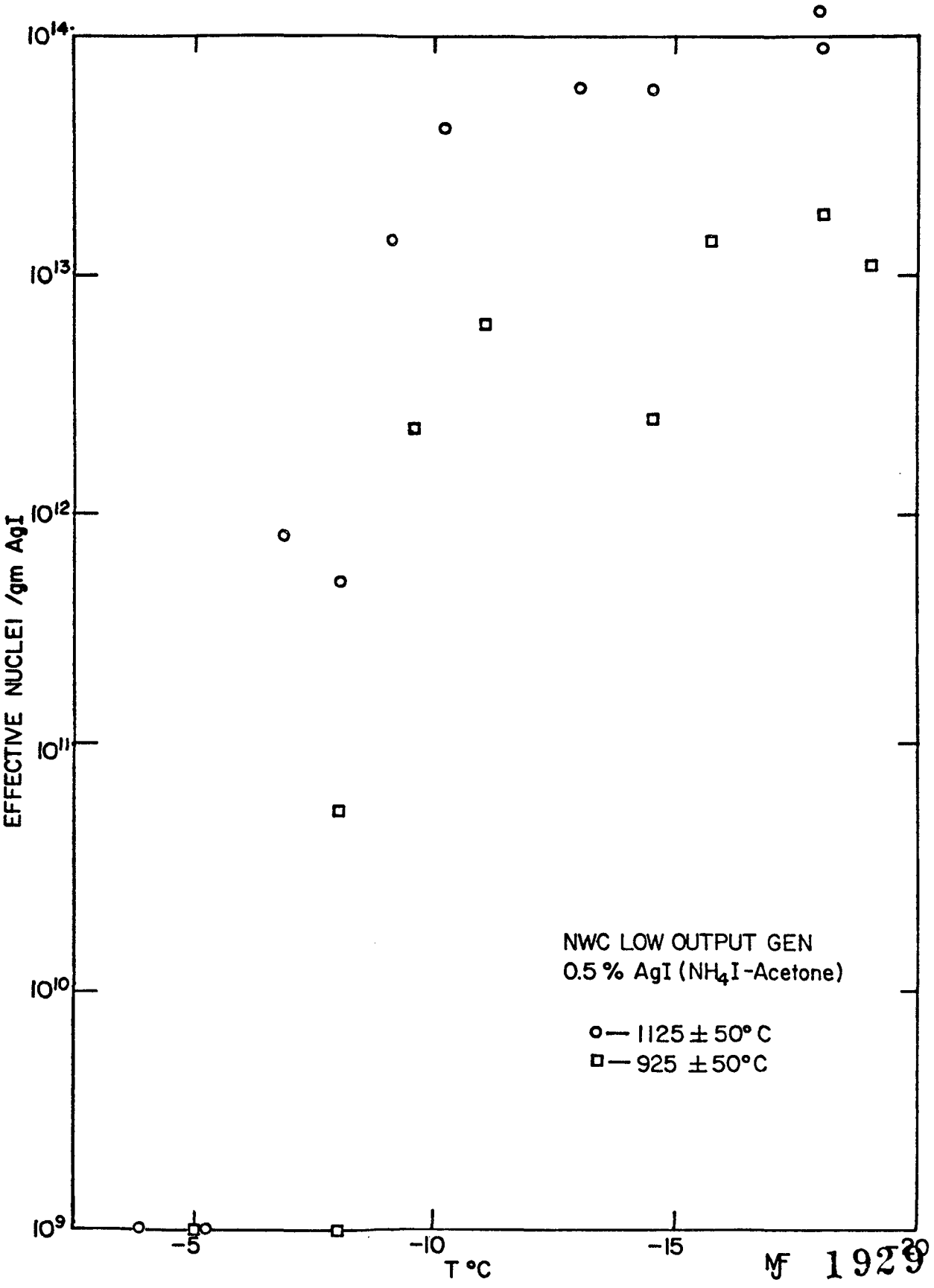


Figure 15. Nuclei activity-temperature plot of 1/2% AgI concentration.

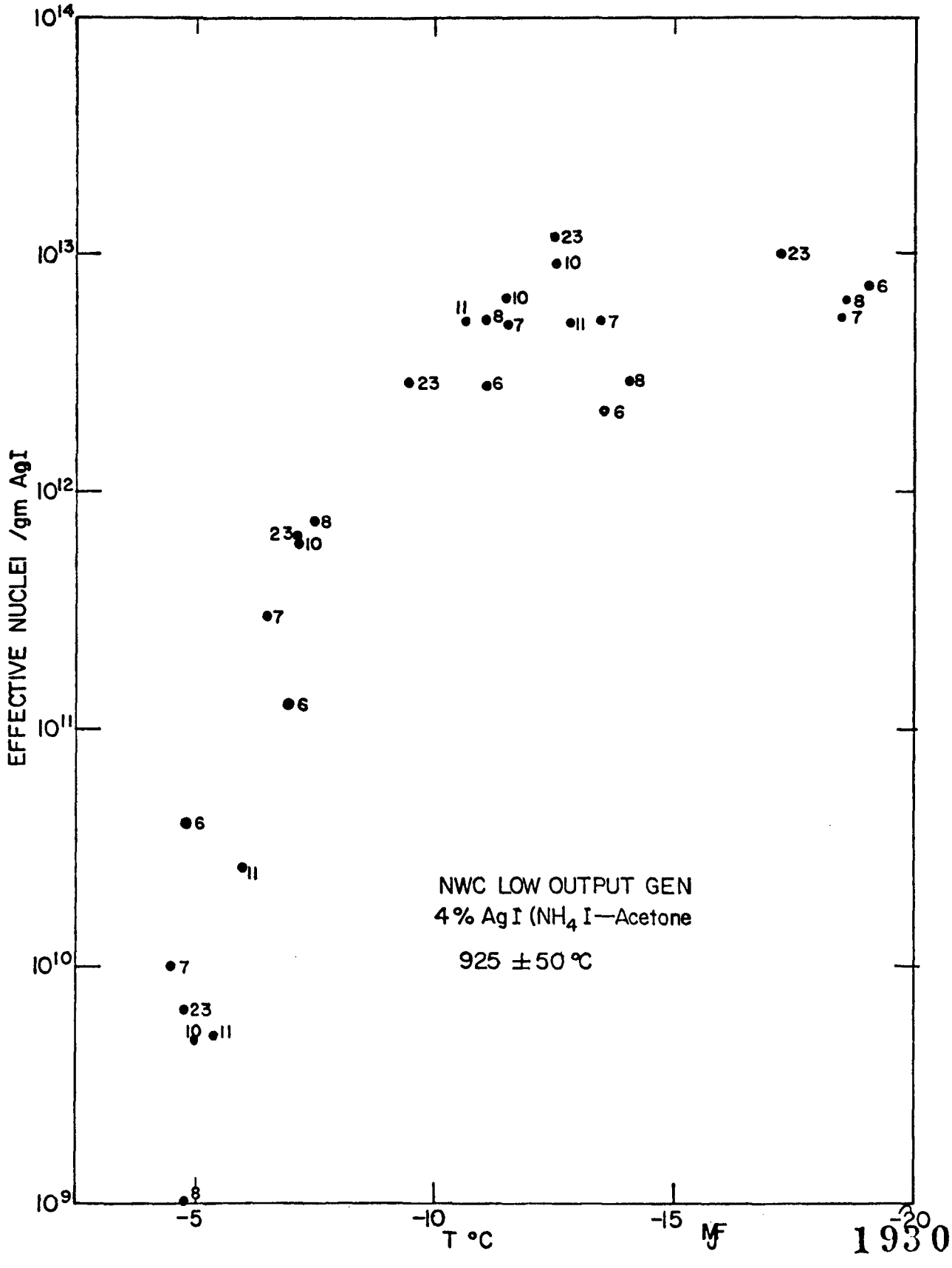


Figure 16. Nuclei activity - temperature plot for 4% AgI concentration. Cool flame.

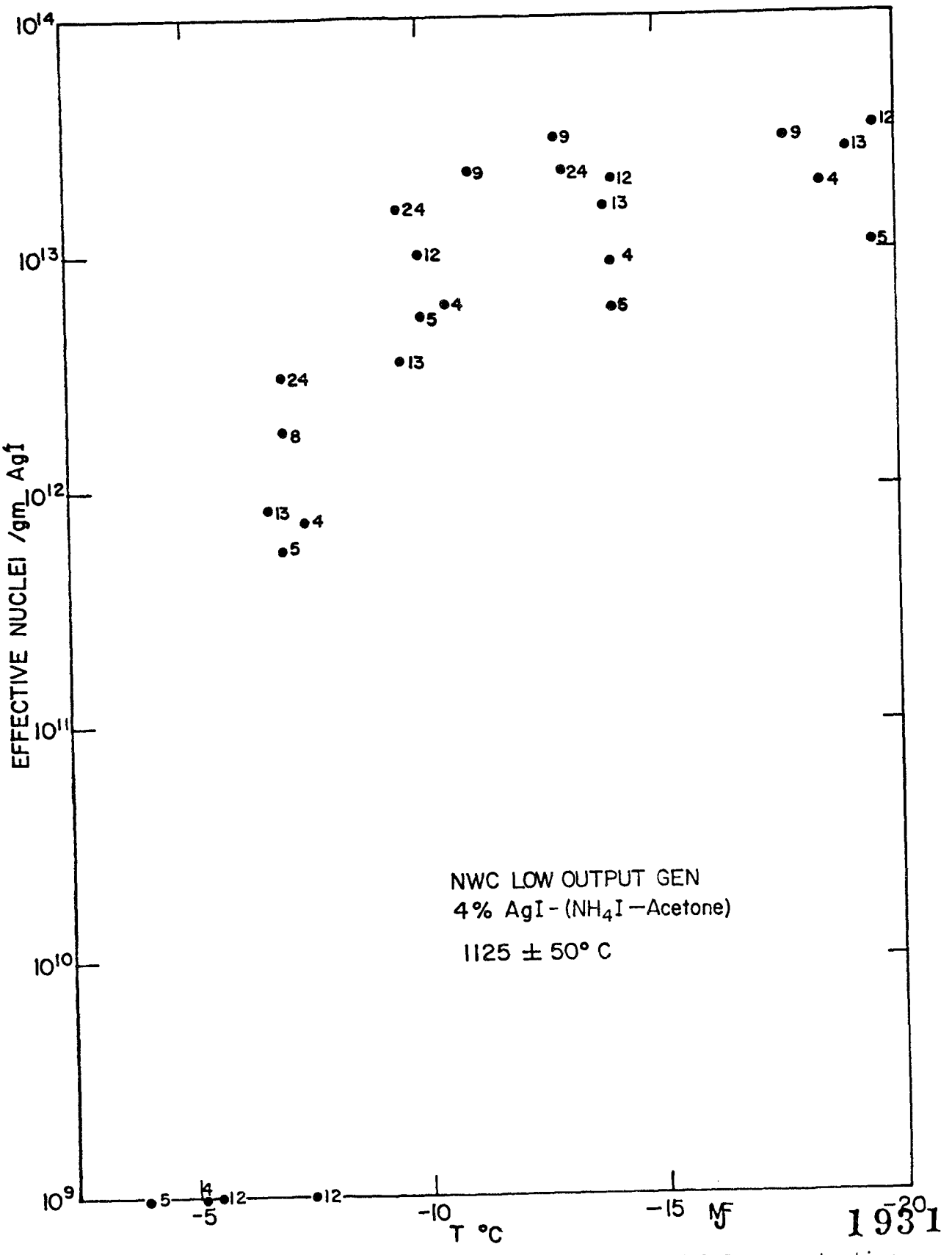


Figure 17. Nuclei activity - temperature plot for 4% AgI concentration. Hot flame.

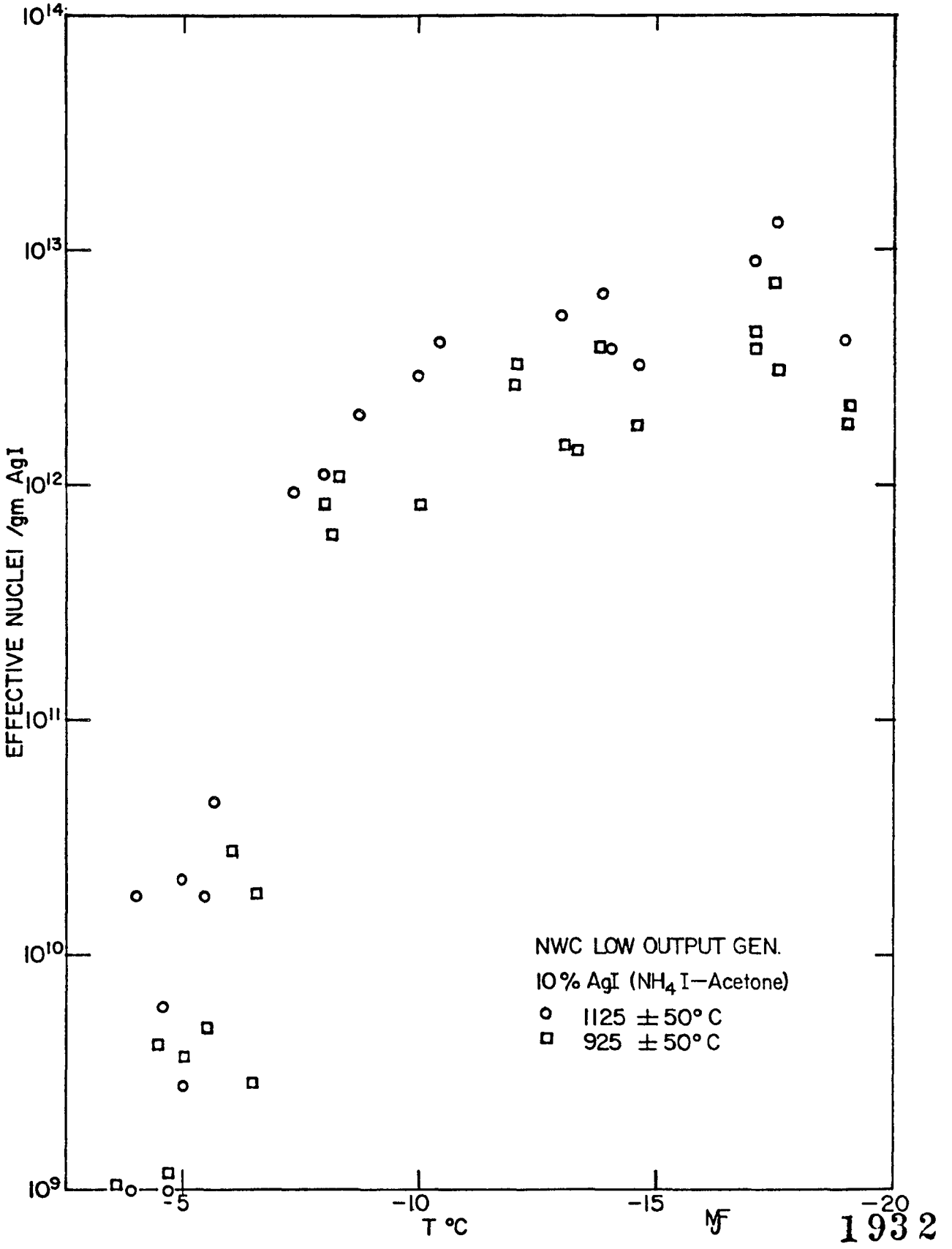


Figure 18. Nuclei activity-temperature plot for 10% AgI concentration.

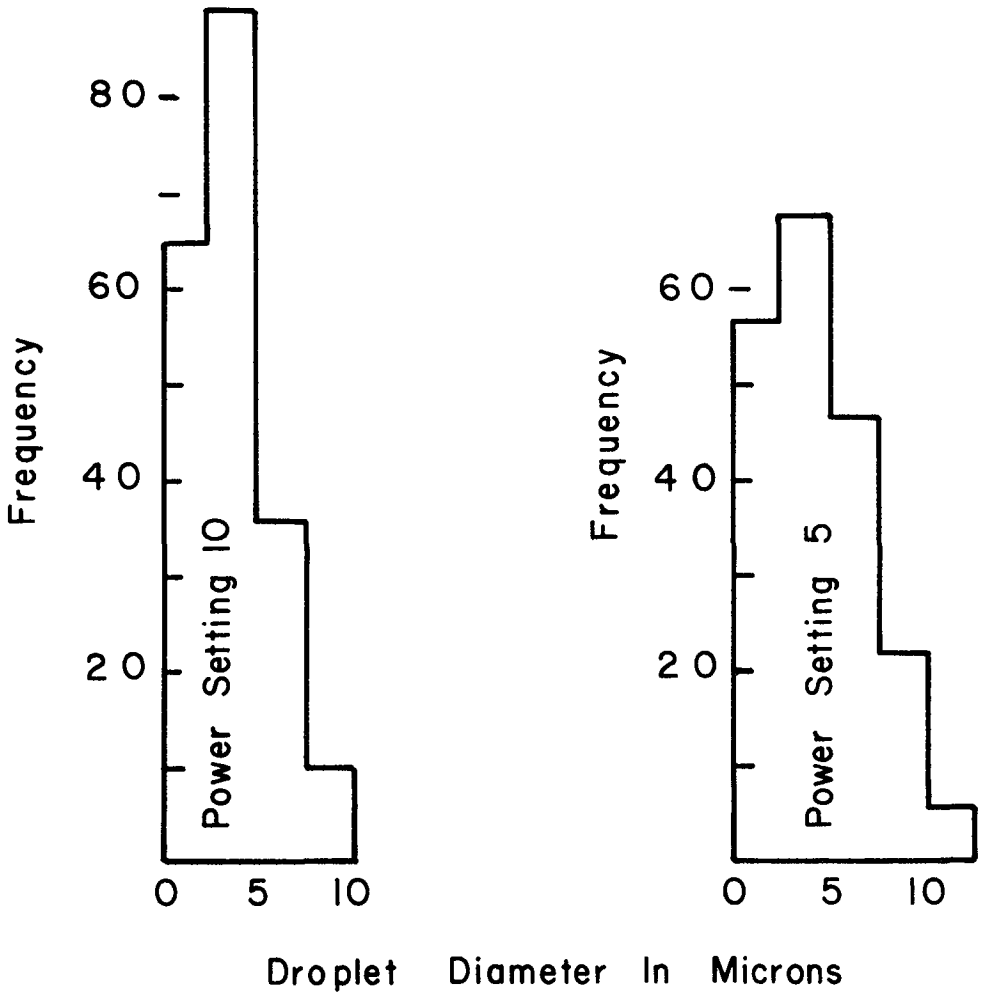


Figure 19. Frequency distributions for 200-count samples of fuel droplets obtained from low output generator. Power setting 10 for cool flame and power setting 5 for hot flame.

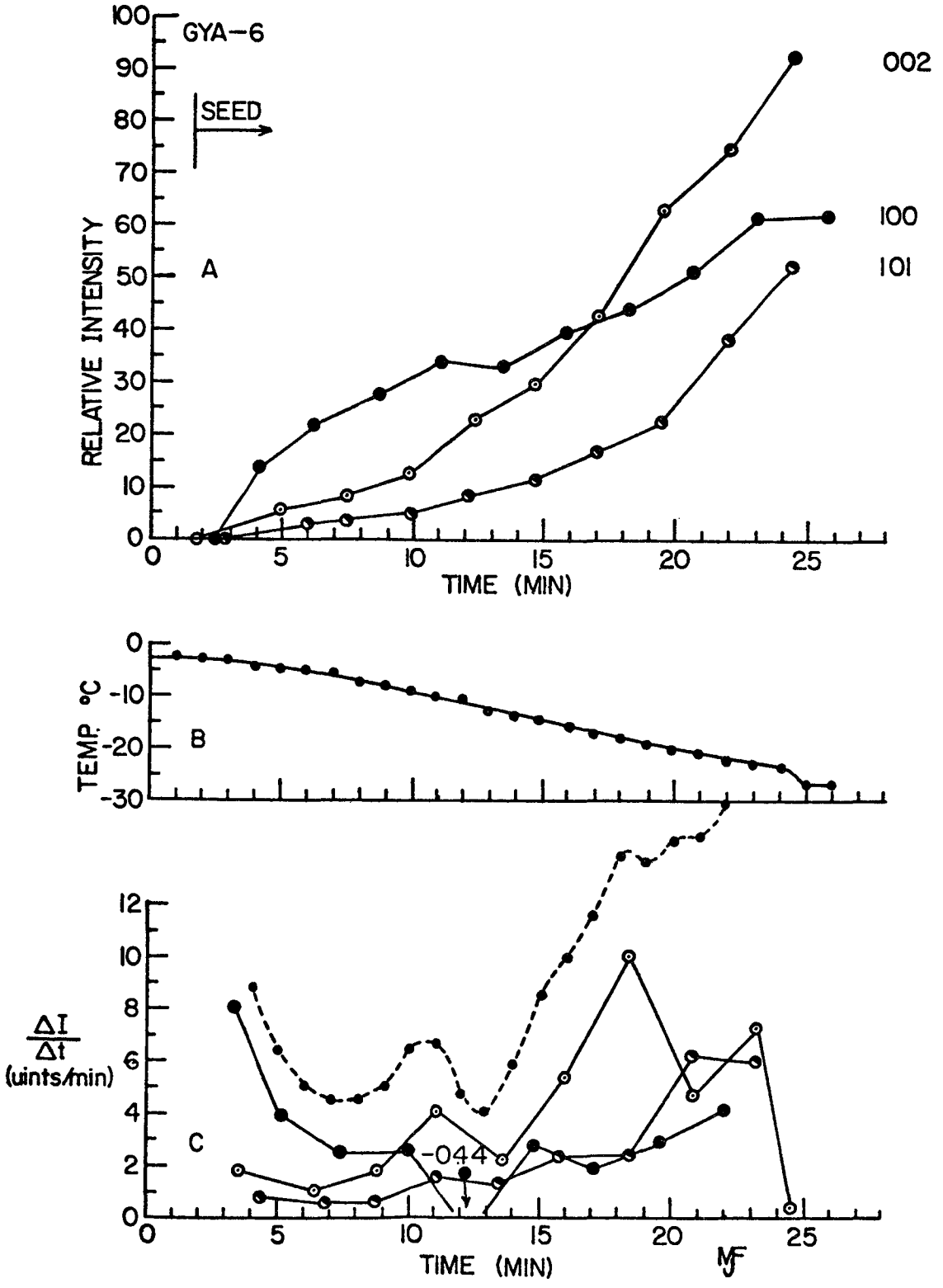
the flame. Calculations made from other generators also indicate that a 1:1 droplet-particle relationship cannot exist but that many AgI particles must result from the single solution drop produced by the jet of the burner. Obviously, discussion on this topic must remain speculative until considerably more experimentation can be carried out.

Further Observation of the -12°C Anomaly

A possible reduction in nucleation efficinecy of AgI aerosols in the region -10 to -15°C has been reported by St.-Amand (1967) and by Davis (1971), and has been suspected to exist by others (G. Langer and R. Layton, personal communication). It was mentioned in previous sections that a few of the data indicated an activity drop in this vicinity, but because of the lack of sufficient data in this region such results are inconclusive.

A series of three experiments were performed using the x-ray diffraction cloud chamber (Davis, 1968); aerosols obtained from the low output generator were carried from the generator into the nucleation studies laboratory by a vertical conduit. The generator was mounted on a hooded pedestal outside of the laboratory and the aerosols carried into the conduit by means of a high performance circulation pump. Dilution of the aerosol prior to injection into the chamber was of the same order of magnitude as that reported by Davis (1971), although exact measurement was made impossible by the nature of the arrangement below the conduit. Tests were made prior to the experiments to observe whether or not a flooding of the chamber with excessive aerosol would take place. The amount injected was reduced to the point where the photocell fog monitor indicated significant fog remaining in the chamber during the run.

These three experiments labeled GYA-6, GYA-7, and GYA-9 are illustrated in Figures 20 through 22, respectively. In these experiments the aerosol and fog were simultaneously and continuously (or at close increments) injected into the chamber such that a continuous precipitation of ice from the seeded cloud would take place. Because of the sensitive nature of the detection system it was anticipated that changes in the rate of intensity increase of the prominent 002 and 110 ice peaks would be sufficient to detect the anomaly. The value of the first derivative (approximated by the first finite difference) for successive oscillation scans of the peaks when plotted against time would yield minimum values at the anomaly. As the temperature of the chamber is gradually reduced the anomaly should show up by a retardation or arresting of the increase in x-ray scattering due to fallout of ice. There may be a 1-2°C lag in the position of the anomaly. In all cases the 100 reflection shows a strong dip in the first difference plot in the vicinity of the anomaly (as indicated by upward projection of the minima into the temperature curve above it). The region of minima is somewhat complex in some cases, although the "spike" observed within the minima of Figures 20 and 22, for example, is probably fortuitous. A better indicator of volume change of intensity is given by the sum of the first differences for the three reflections, 002, 100, and 101 (inasmuch as a change in ice habit could result in a retardation of intensity for one reflection but an increase in another reflection). An interesting feature of these diagrams is the initially stronger intensity of the prismatic reflection (100) early in the run and



1934

Figure 20. Intensity and first derivative plots of ice crystal fallout vs. time for descending chamber temperature. GYA-6.

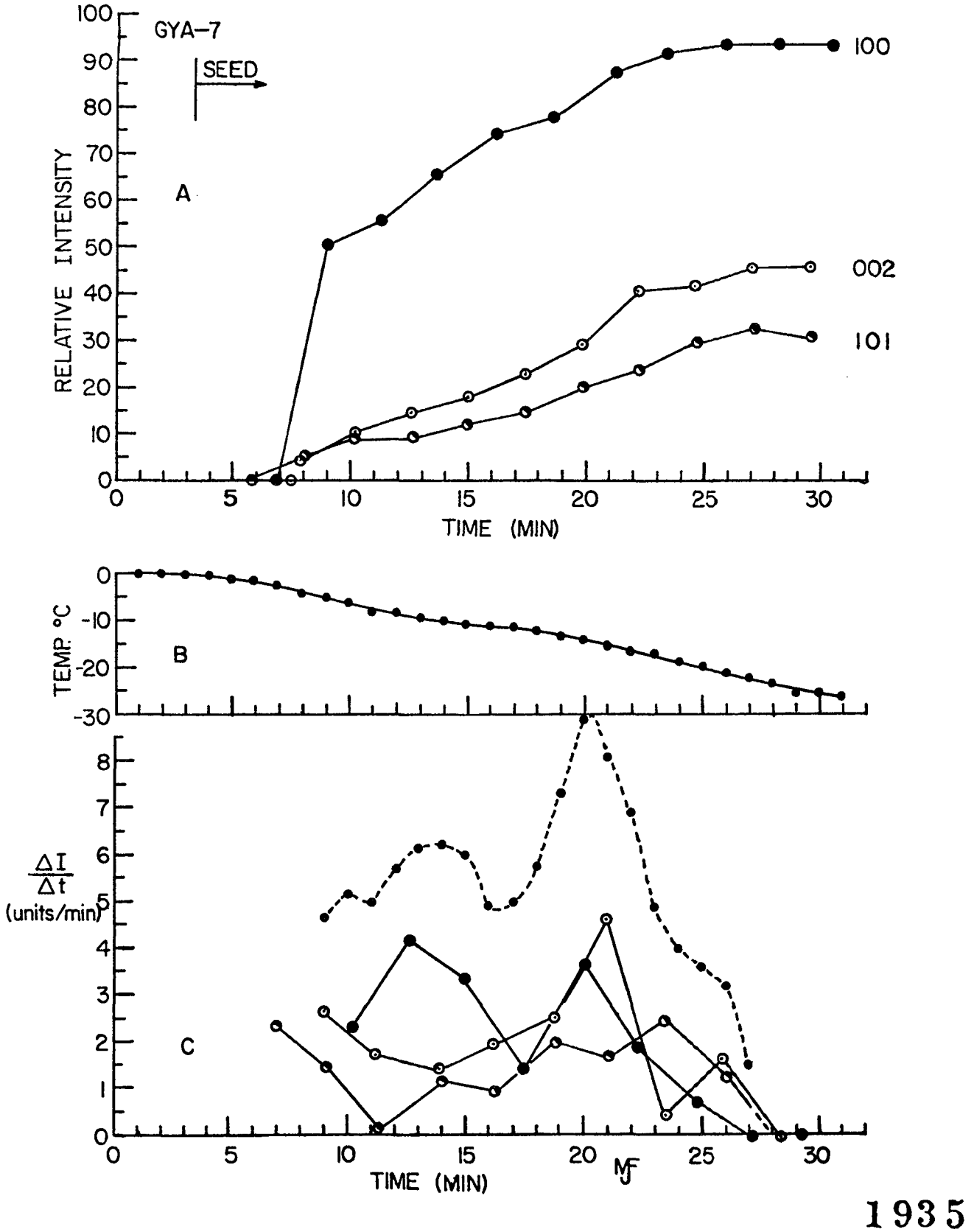


Figure 21. Intensity and first derivative plots of ice crystal fallout vs. time for descending chamber temperature. GYA-7.

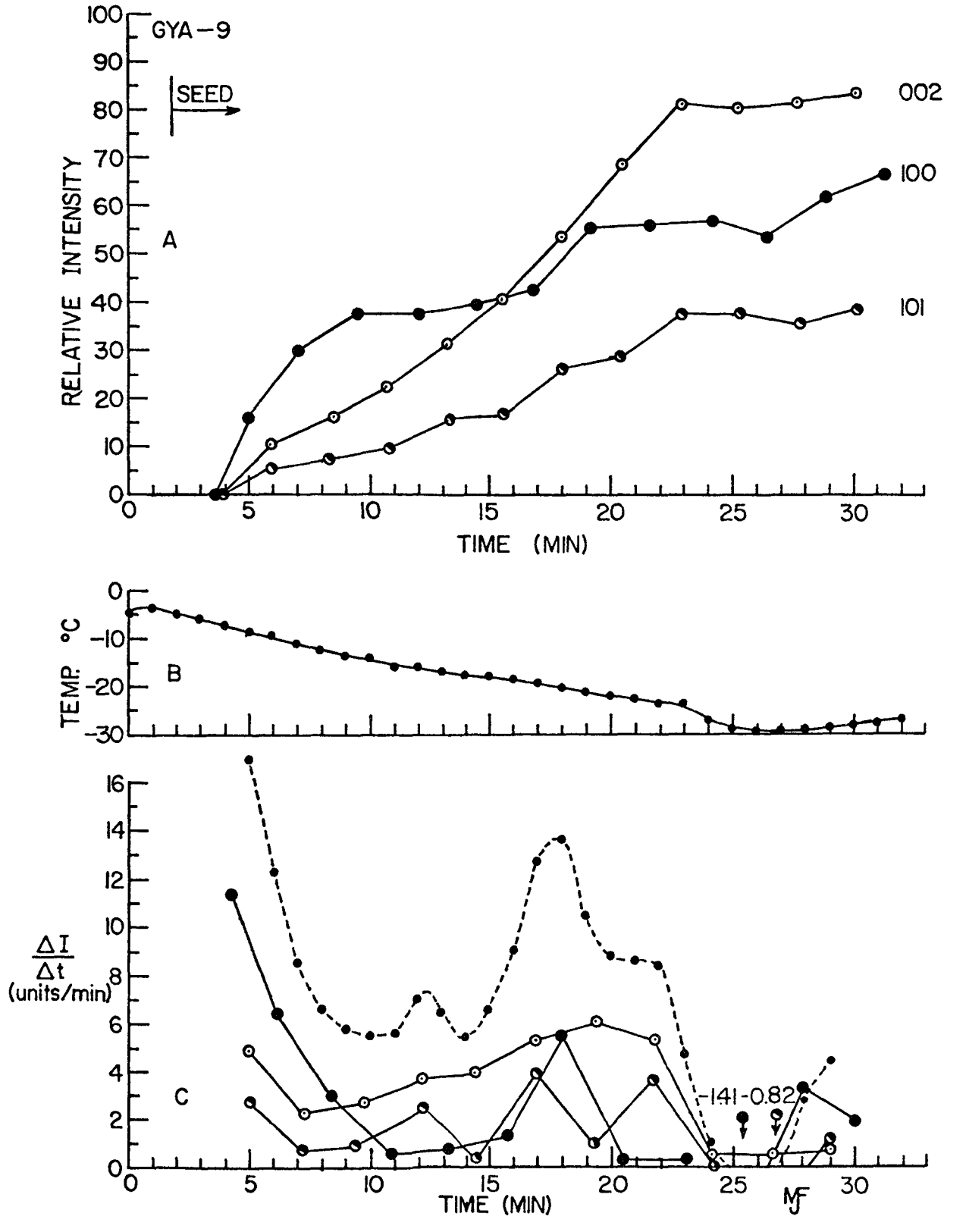


Figure 22. Intensity and first derivative plots of ice crystal fallout vs. time for descending chamber temperature. GYA-9.

an increase of the 002 intensity at lower temperatures until it becomes the dominating reflection. This is in agreement with the general trend of prismatic habit development at the warmer temperatures and plate-like development at the lower temperatures. The sharp drop in increase in intensity at the end of the experiment is caused by absorption effects developing as the ice layer becomes "infinitely" thick. The intensity changes diminish because the "transparency" limit of the sample has been exceeded (Davis, 1971, page 100).

These three experiments give additional support to the existence of a physical anomaly in a nucleation process at -12°C or vicinity. It cannot be concluded from this study that the anomaly results from a surface or physical property of the AgI itself, or rather from the growth mechanism of ice at -12°; other considerations (such as thermal conductivity of ice) lead one to suspect the latter as being correct.

Comparison of the AgI-NH_4I-Acetone Systems with the AgI-NaI-Acetone System

Figures 23 and 24 present two additional experiments comparing the ice nucleating ability and complexing tendency of each of the two aerosols commonly used in cloud seeding, the AgI aerosols obtained from NH_4I complexing solutions and the AgI-NaI aerosol. These experiments were performed under the "tent" of a thermoelectric cooling device mounted in the x-ray diffractometer and operates on the same principle as the x-ray diffraction cloud chamber discussed previously. The major difference is the smaller volume of this system and the capability of using longer wave-length radiation.

In Figure 23 the sodium iodide is eliminated after two minutes in a combination with AgI to form complex F (Johnson and Davis, 1972). Two reflections of this complex were observed to exist in the region of oscillation and their presence indicates the formation of the complex at the expense of part of the AgI and all of the NaI. A reduction in about 50% of the free silver iodide in this aerosol is obvious. Also of note is the fact that ice occurred only after the temperature had reached -15°C several minutes following the saturation level in the chamber. It can be observed in Figure 24, however, that ice occurred at approximately -7°C and only approximately 3 minutes following saturation. The most significant aspect of Figure 24 is the lack of reduction of AgI beyond the 90+% level initially present in the aerosol (the 10% reduction being in part fictitious and caused by instrumental factors).

The great advantage in using the NH_4I system for cloud seeding activities is further substantiated by these additional experiments.

CONCLUSIONS AND RECOMMENDATIONS

This investigation has revealed a number of interesting characteristics of AgI aerosols obtained from AgI-NH_4I solutions. The type of generator used has the characteristics of producing a narrower size distribution of aerosol particles than most other types of field and airborne generators. It is possible that further design and modification of this device could

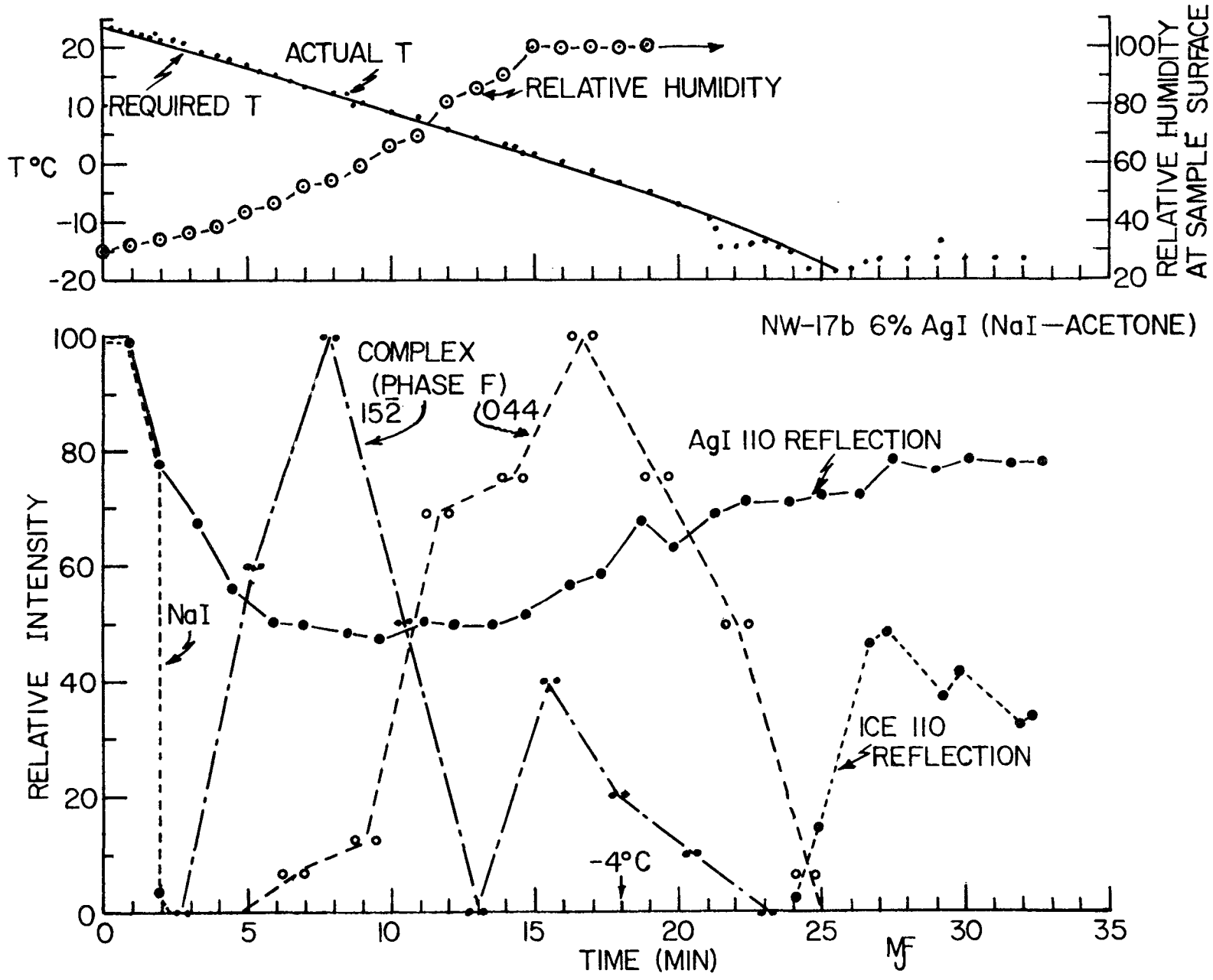


Figure 23. Complexing and nucleation characteristics of AgI-NaI aerosols. X-ray cloud chamber system.

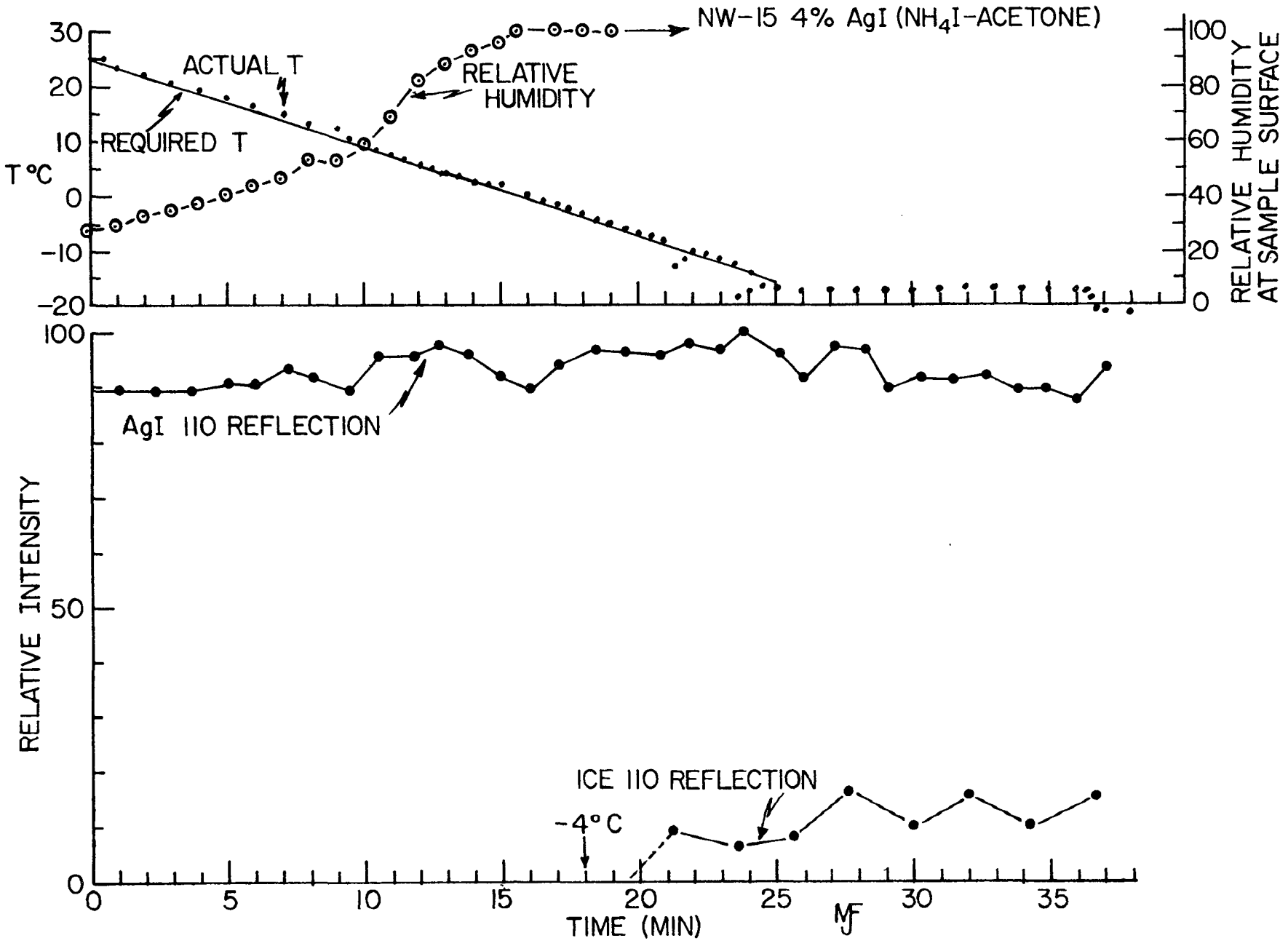


Figure 24. Complexing and nucleation characteristics of AgI aerosols from AgI-NH_4I system. X-ray diffraction cloud chamber.

give even a more restricted size distribution. Further design work in this area would be desirable for the purpose of allowing the field operator to control the phase and size of particulate matter that he wishes to introduce into the cloud.

The results of this study also include the interesting concept of an activity anomaly in the vicinity of -10 to -15°. This work is in agreement with previous studies showing similar behavior of other aerosols including those associated with sodium iodide. Another feature of the AgI aerosol obtained from ammonium iodide-bearing solutions is its greater activity at the higher temperatures (e.g., -5°C) in the cloud. Further physical and chemical sutdies of these aerosols are very desirable in order to understand the reasons for its unusual nucleation ability.

ACKNOWLEDGEMENTS

We gratefully acknowledge the helpful discussions of J. Carroz and I. Koff of the Naval Weapons Center, China Lake, California. This research was supported by the Naval Weapons Center, Office of Naval Research, Contract No. N00123-72-C-0263.

- - - - -

REFERENCES

Beeman, W. W., P. Kaesberg, J. W. Anderegg, and M. B. Webb, 1957: Size of particles and lattice defects. Handbuch der Physik, 32, 321.

Davis, B. L., 1968: Ice crystal sizes and settling velocities determined with an x-ray diffraction cloud chamber. The Norelco Reporter, 15, 17-21.

Davis, B. L., 1971: In Situ x-ray analysis of ice crystal fallout from seeded clouds. J. Atmos. Sci., 28, 99-101.

_____, and D. N. Blair, 1969: The role of substrate strain in ice nucleation. J. Geophys. Res., 74, 4571-4580.

_____, and R. L. Petersen, 1970: Unusual polytypism in AgI. Crystal Lattice Defects, 1, 275-276.

dePena, R., and E. A. Caimi, 1967: Hygroscopicity and chemical composition of silver iodide smoke used in cloud seeding experiments. J. Atmos. Sci., 24, 383.

Donnan, J. A., D. N. Blair, and D. A. Wright, 1971: A wind tunnel/cloud chamber facility for cloud modification research. J. Wea. Mod., 3, 123-133.

Guinier, A., and G. Fournet, 1955: Small angle scattering of x-rays. John Wiley and Sons, Inc., New York, 83.

Johnson, L. R., and B. L. Davis, 1972: Particle size determination. Third Conf. on Wea. Mod., Amer. Meteor. Soc., Rapid City, South Dakota, June 26-29, 1972, 18-23.

_____, _____, and D. N. Blair, 1972: Silver iodide aerosol studies: Part I. Analytical techniques and brief review of theory. Tech. Rept. R72-15(i) Institute of Atmospheric Sciences, S. D. School of Mines and Technology, Rapid City, S.D.

Koff, Irwin and P. St.-Amand, 1971: Uniform Size Particle Generator. Proceedings of the International Conference on Weather Modification, Am. Meteorol. Soc., Canberra, Australia, 6-11 Sept. 1971, 356-357.

Mossop, S. C., and C. Tuck-Lee, 1968: The composition and size distribution of aerosols produced by burning solutions of AgI and NaI in acetone. J. Appl. Meteor., 7, 234.

Ono, A., and R. Kimura, 1967: An x-ray diffraction study of silver iodide from aerosol generators and a preliminary experiment on ice nucleating ability of β-AgI and γ-AgI. J. Meteor. Soc. Japan, 45, 157-165.

Petersen, R. L., and B. L. Davis, 1970: Determination of crystallite size and anelastic strain in various types of generator effluent. Proc. Cloud Physics Conference, Fort Collins, Colorado, August 24-27, 1970, 27-28.

Petersen, R. L. and B. L. Davis, 1971: Determination of crystallite size and anelastic strain in various types of generator effluent. J. Geophys. Res., 76, 2886-2890.

St.-Amand, P., 1967: Nucleation by silver iodide and similar materials. Proc. Conf. I: Project Skywater, 10-12 July 1967, Denver, 305-346.

Smith, D. J., and K. J. Heffernan, 1954: Airborne measurements of the concentration of natural and artificial freezing nuclei. Quart. J. Roy. Meteor. Soc., 80, 182-197.

Steele, R. L., and F. W. Krebs, 1967: Characteristics of silver iodide ice nuclei originating from anhydrous ammonia-silver iodide complexes. J. Appl. Meteor., 6, 105.

Warren, B. E., 1955: A generalized treatment of cold work in powder patterns. Act. Crystallog., 8, 483-486.

Wilson, A. J. C., 1949: X-ray Optics. London, Methuen and Company, Ltd., 1949.

- - - - -

A BENCHMARK NETWORK FOR ICE NUCLEUS COUNTS

Paul A. Allee

Atmospheric Physics and Chemistry Laboratory
National Oceanic and Atmospheric Administration
Boulder, Colorado 80302

It is important for the atmospheric scientist to know the concentration of atmospheric ice nuclei and the variation of those concentrations with time. These nuclei are involved in the process of converting supercooled water clouds to ice clouds and any theoretical consideration of weather modification processes must be concerned with their presence in the atmosphere. Measurements to determine the atmospheric concentrations of ice nuclei have been made at many specific locations for varying time periods. However, organized large scale measurements of the atmospheric ice nuclei concentration, coordinating a number of widespread specific sites over a considerable interval of time, have been carried out by only a few projects.

Bowen (1958) reported on the results of a one-month examination of the simultaneous concentrations at eight stations, six Australian, two in the United States. Bigg and Miles (1964) carried out a lengthy experiment in which simultaneous measurements of ice nucleus concentrations were made at 24 locations in eastern Australia. Kline (1964) reported on extensive measurements derived from a cooperative ice nuclei observational program at 15 locations in the United States during the period from 1959 to 1962. His results give evidence of a geographical difference in ice nuclei concentrations. The most comprehensive survey of the global distribution of ice nuclei concentration was reported by Bigg and Stevenson (1970) at 44 locations during January, February and March of 1969. A three station network in the north Pacific Ocean during portions of 1968 and 1969 has detected the advection of enhanced ice nuclei concentrations eastward across the Pacific Ocean (Hobbs, Bluhm and Ohtake, 1971).

In 1970 the Bureau of Reclamation of the Department of Interior requested that the National Oceanic and Atmospheric Administration (NOAA) establish a benchmark network for ice nuclei counts. The purpose of the network being established is to determine the climatological mean and variation for the ice nuclei concentration throughout the seventeen westernmost states and the north Pacific Ocean. The network will consist of field monitors located at approximately twenty National Weather Service locations selected as most likely to be free from anthropogenic sources of ice nuclei. Fig. 1 is a map showing the location of the field monitor sites, identified according to the National Weather Service call letters assigned as location identifiers.

The instrumentation of the network consists of two parts:

(1) The equipment for collecting ice nuclei at the field monitoring site. Fig. 2 is a view of the mechanism within the outdoor field monitor. The major components above the base plate are the timer, the vacuum pump, the airflow meter, the elapsed running time meter and shield covering the barrier terminal strip. Below the base plate are the power switch and test switch controls, and the plastic capsule containing the membrane filter. A cover protecting the components has windows for viewing the flow meter and the elapsed time meter. Its lower edge is even with the lower edge of the filter capsule.

(2) The thermal diffusion chamber for the measurement of ice nuclei concentrations. This equipment located at Boulder, Colorado, and a duplicate of that described by Gagin and Aroyo (1969), activates the ice nuclei on the membrane filter for counting.

The field monitor is designed to filter air through a membrane filter at a known time-rate. The membrane filter has such a small pore size (less than one micron diameter) that most of the particulates of the atmosphere that are classed as ice nuclei are collected on the surface of the membrane filter. The field monitor unit is designed to accomplish this with a minimum amount of attention, yet still furnish control of the time and rate of air flow through the membrane filter. Two types of field monitors are available: outdoor and indoor. The outdoor model is the preferred installation since it is farther removed from buildings, which under some circumstances can be a source of non-natural ice nuclei.

The timer of the monitor is set so that air will be drawn through the membrane filter for a few minutes of each hour for each of the twenty-four hours of the day. Thus, the particulate sample obtained on a membrane filter that is changed daily will be representative of the conditions present throughout a twenty-four hour period. The time intervals of pump operation and air flow are coordinated so that about 300 liters per day (to be calculated from the elapsed time meter and flow meter readings) will pass through the filter.

It is planned that the filter will be changed daily at midnight, local time, or as near thereto as possible. The daily representative ice nuclei concentration can then be compared to the daily weather records obtained by the cooperating National Weather Service station for any correlation or anomalies that are weather dependent. When a sufficient number of exposed capsules have been accumulated they will be mailed to the Atmospheric Physics and Chemistry Laboratory at Boulder, Colorado, for processing. After preparation the filter is placed in a subfreezing

thermal diffusion chamber, and the ice nuclei are subjected to an environment that is saturated with respect to water (supersaturated with respect to ice). The ice nuclei become the centers of growth of ice crystals which are then grown to visible sizes and counted.

The investigation of the ice nuclei concentrations by Hobbs, Bluhm and Ohtake (1971) indicates that the time of variation of the climatological ice nuclei concentration is on a greater-than-one-day time scale. Accordingly, it is proposed that the filters from a station be activated at -15°C and -20°C on alternate days. This will give ice nuclei concentration data for two temperatures, yet not interfere seriously with the expected climatological variation time scale. This scheme will also reduce the hazards of bookkeeping and contamination due to handling that would result from cutting filters in half for processing at the two temperatures. It is expected that in excess of 7500 filters will be analyzed during the first year of this project. The program will be reviewed at that time to determine the feasibility of operation of the network for a second year.

- - - -

Bibliography

Bigg, E. K., and G. T. Miles, 1968. The results of large-scale measurements of natural ice nuclei. J. Atmos. Sci., 21, 396-403.

Bigg, E. K., and C. M. Stevenson, 1970. Comparison of concentrations of ice nuclei in different parts of the world. J. Rech. Atmos., Vol IV, 2^{e} annee, no. 2., 41-58.

Bowen, E. G., 1958. Freezing nucleus measurements in January 1957. Aust. J. Phys., 11, 452-455.

Gagin, A., and M. Aroyo, 1969. A thermal diffusion chamber for the measurement of ice nuclei concentrations. J. Rech. Atmos., Vol. IV, 1re annee, no. 3., 115-122.

Hobbs, P. V., G. C. Bluhm and T. Ohtake, 1971. Transport of ice nuclei over the north Pacific ocean. Tellus, XXIII (1971), 1, 28-39.

Kline, D. B., 1963. Evidence of geographical differences in ice nuclei concentrations. Mon. Wea. Rev., 91, 681-686.

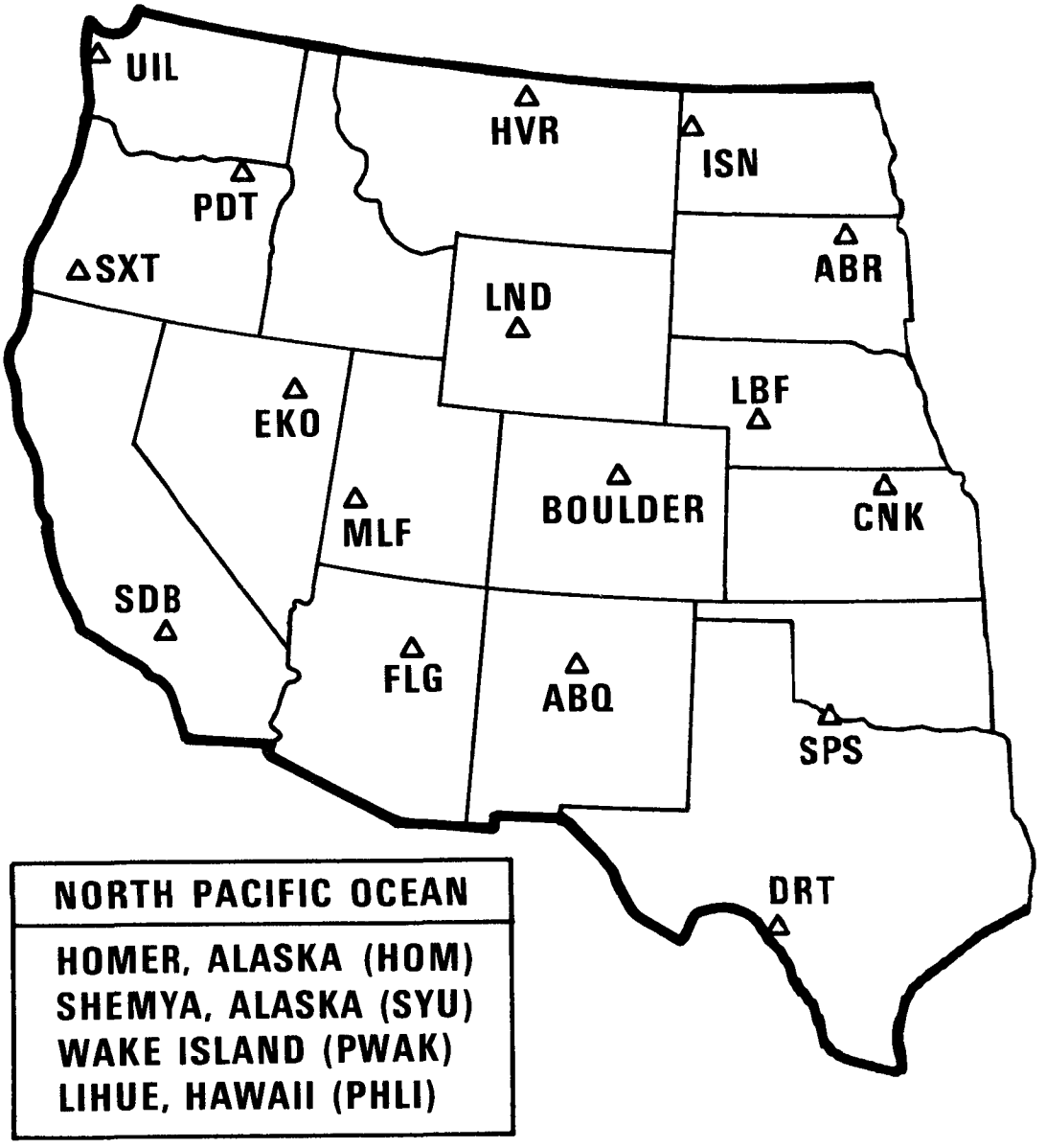


Figure 1.

Benchmark Network for Ice Nucleus Counts

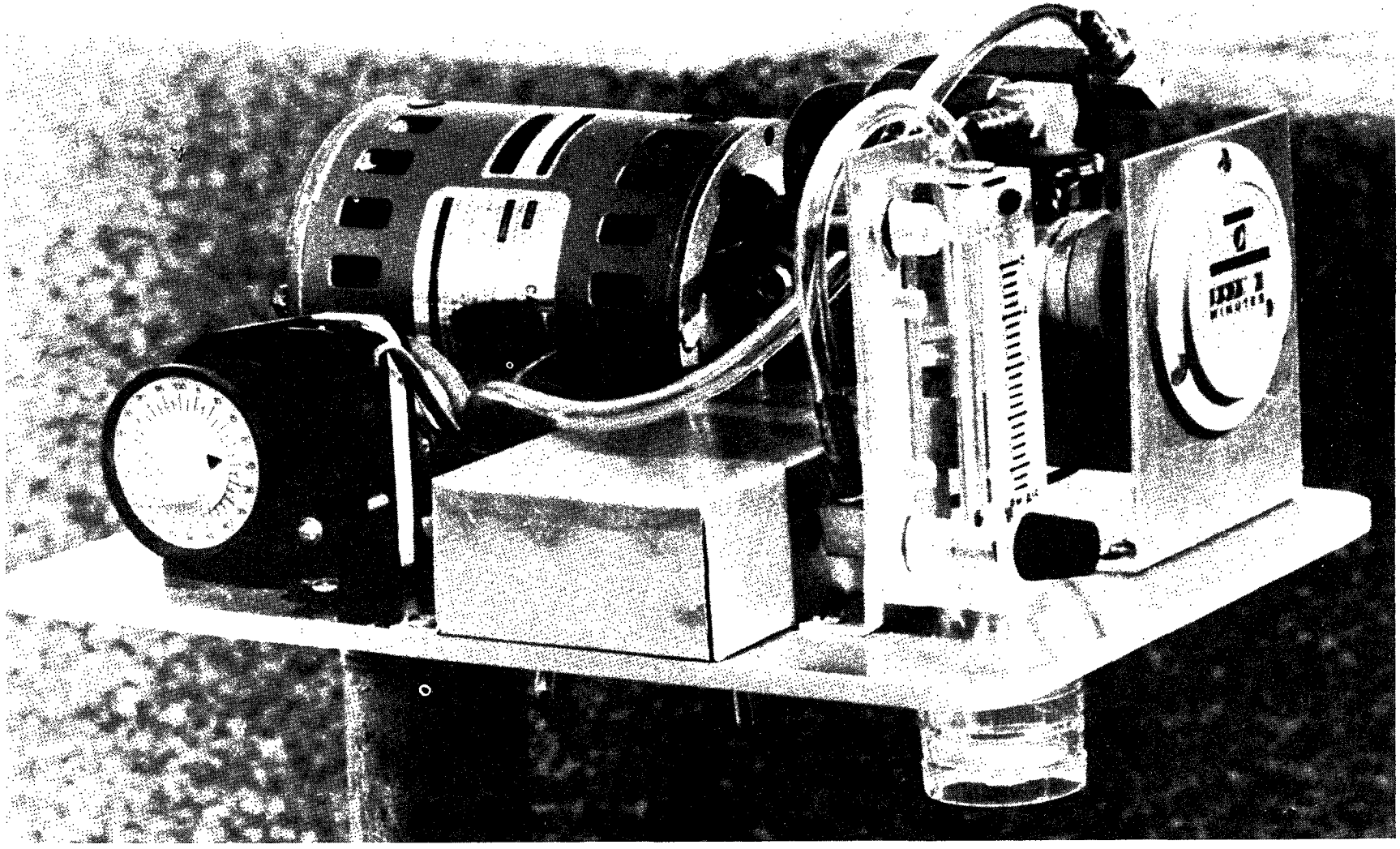


Figure 2.

Top View of Outdoor Field Monitor, Without Cover

FIELD COMPARISONS OF ICE NUCLEUS MEASUREMENTS BY THREE METHODS

C. A. Grainger
A. B. Super

Montana State University
Bozeman, Montana

1. INTRODUCTION

The concentration of ice nuclei plays a very fundamental role in most weather modification experiments. As more knowledge is gained in the field of weather modification, the importance of knowing ice nucleus concentrations, both naturally and after seeding, is becoming more apparent. In attempting to measure this quantity, it is desirable to be familiar with the field performance of the various techniques that are available for ice nucleus monitoring so that a rational choice of measurement method can be made and the resulting data can be properly interpreted.

Ice nucleus concentrations were measured in conjunction with weather modification experiments carried out in the Bridger Mountains near Bozeman, Montana. A detailed discussion of these experiments is given by Super et al.(1972). The experimental area is shown on Figure 1. Measurements were made at the Bangtail Mountain Observatory (BMO) during the 1971-72 winter field season by three independent methods. This was done in an effort to see if it was possible to detect artificial ice nuclei at the BMO, thus demonstrating that the seeding material, released from two sites west of the Main Ridge, was being transported to the primary target area on the Bangtail Ridge east of the Main Ridge.

The seeding methods used included ground-based generators, rocket-carried pyrotechnics, and pyrotechnics dropped from aircraft. However, the large majority of ice nucleus concentration measurements were made while the two ground-based generators were being utilized. These were modified Skyfire generators that burned AgI complexed with NH_4I in acetone at a consumption rate of 30g AgI hr^{-1} for each generator. These generators were also used when ice nucleus measurements were taken by aircraft as will be discussed.

Most of the ice nucleus concentration measurements taken at the BMO were made when the Main Ridge, and usually the seeding sites and BMO as well, were in cloud. The measurements taken by aircraft over the Bridger Range were made when the mountains were well below cloud base.

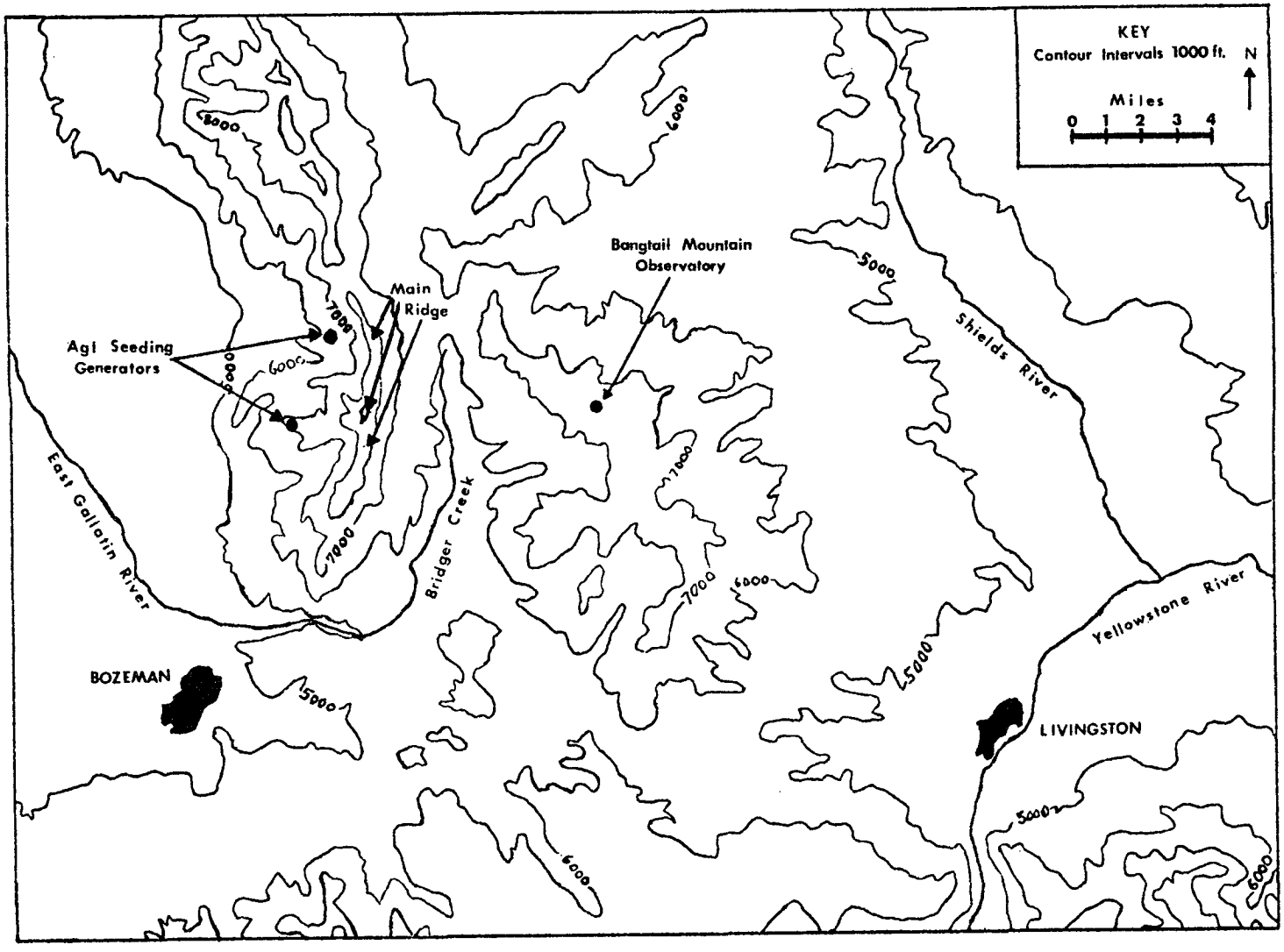


Figure 1. Experimental area in the Bridger Mountains

2. DETECTION METHODS

There are three methods of ice nucleus detection that are commonly used in monitoring ice nucleus concentrations in the field. These are:

a. The use of a Bigg-Warner type rapid expansion chamber.

b. The use of an NCAR acoustical counter.

c. The millipore filter technique.

The Bigg-Warner rapid expansion chamber, described by USWB (1959) and Kline and Brier (1961), consists of a cylindrical refrigerated chamber with a shallow tray of sugar solution at the bottom. The volume of the chamber is ten liters and its walls are normally kept at a temperature of about -10C. Sample air is drawn into the chamber, the chamber is pressurized, and the air is allowed to come to thermal equilibrium with the walls. The pressure is then suddenly reduced to atmospheric by allowing some of the air in the chamber to escape through a release valve. This expansion cools the air and creates a fog for a brief time (15-30 sec) in the chamber. Any ice crystals that form fall into the sugar solution in the bottom of the chamber and grow to visible size. The crystals are then counted in order to arrive at an estimate of the ice nucleus concentration. The temperature at which the ice nuclei are active is computed by assuming the expansion between the two known pressures to be moist adiabatic.

The NCAR acoustical counter, described by Langer et al. (1967) is a continuous measurement device through which the sample air is continuously drawn. The sample air is humidified and then cooled in a refrigerated chamber, forming a supercooled cloud. The air passes out the bottom of the chamber through a small capillary tube. Any particles that are 20 μm or greater in diameter will make an audible "click" as they pass through the tube. Most ice particles that form in the cloud will grow to this size by the time they reach the bottom of the chamber but the water droplets in the cloud will not. The number of ice particles are counted by means of a sensitive microphone and an electronic counter.

The millipore filter technique that was used has been described in some detail by Stevenson (1968). A known volume of sample air is drawn through a millipore filter. A pore size of 0.45 μm is commonly used, although this varies from user to user. The pores of the filter are then filled with melted petroleum jelly from the exhaust side of the filter and the filter is placed in a supersaturated environment at the desired temperature. Ice crystals are then allowed to grow on the nuclei that are on the filter to a size that can be seen with a low power microscope. The number of ice nuclei in the air sample is then assumed to be equal to the total number of ice crystals visible on the filter.

These three methods are commonly used and were basically the techniques that were used at the BMO. There were, however, several ways in which the methods employed at the BMO differed from the norm. These are noted below.

The Bigg-Warner counter used was a standard USWB version of this instrument, but with several modifications made by Dr. G. Langer of NCAR. One of the changes was that two air pumps were used. One drew the sample air through the chamber and the other forced air through a filter system and into the chamber. There was no danger of contamination from the pumps when using this instrument since the sample air passed through the chamber before passing through a pump, and the air which passed through the pressurization pump was filtered before introduction into the chamber. It was necessary, however, to account for the dilution of the sample air by the filtered air in the computation of the ice nucleus concentrations. This was easily accomplished using a multiplicative factor dependent upon the preexpansion pressure.

Another modification of the Bigg-Warner chamber was the installation of a heating element on the bottom of the sugar solution tray. By using this low power heater, the ice in the tray at the end of a measurement could be melted and another measurement made without having to take the tray of sugar solution out of the chamber and replace it again.

An effort was made to increase the humidity of the chamber by mounting strips of blotting paper on the lid of the chamber and keeping this paper moist.

The NCAR counter used at the BMO was a commercial unit manufactured by E. Bollay Assoc. (Model No. 105). At the suggestion of Dr. G. Langer of NCAR (personal communication), the commercial unit underwent several modifications until it closely resembled the instrument described by Langer and Weickmann (1971).

The millipore filters used at the BMO were 0.45 and 0.22 μm equivalent pore size. The filters were sent to the NCAR facilities at Boulder, Colorado and were developed there by Dr. G. Langer. The apparatus used at NCAR has been described by Langer (1971). This method differed from that described by Stevenson (1968) in that the membrane was initially covered by cloud droplets and the air over the filter was supersaturated with respect to ice rather than water. More cloud droplets were introduced into the chamber until no new crystals grew as the result of adding droplets to the filter.

Despite the fact that these three methods of ice nucleus detection have been in common use for some time, there has been little work done in comparing them against one another, especially under field conditions. One of the more comprehensive studies that has been carried out was done at the Second International Workshop on Condensation and Ice Nuclei (Grant, 1971). A considerable amount of disagreement was seen to exist between different types of instruments as well as between different

instruments of the same general type, even under the closely controlled laboratory conditions. The type of nuclei used (i.e., either natural or artificial) apparently made a significant difference when comparing any two detection methods. In the summary of the results of that portion of the workshop that dealt with ice nuclei, Bigg (1971) stated with regard to the rapid expansion chambers used, "Their performance with natural nuclei appeared to be good, but the extraordinarily poor performance of two of the three with thermally generated silver iodide is a very disturbing feature of their operation." With regard to an NCAR counter that had been modified by Dr.G. Langer, Bigg stated, " The remarkably good performance of this counter with natural nuclei and its fair results with artificial nuclei show it to be a great improvement on the earlier commercially produced acoustic counters." In reference to most of the millipore filter methods used he said," They performed much better with natural nuclei than with silver iodide . . ."

The age of the artificial nuclei seemed to make a significant difference to some methods and very little to others. Bigg (1971) showed that the rapid expansion chambers were apparently much more sensitive to the age of the silver iodide nuclei than any of the other methods. The rapid expansion chambers measured rates of decrease in the nuclei concentrations of from one to four orders of magnitude per hour. The NCAR counter and the membrane filter methods typically registered decreases of less than a factor of two over the same time interval. The source of this difficulty is not understood.

Each of three methods described above has its own relative merits as well as disadvantages and there exist people in the field of ice nucleus detection who will support one of these methods and still others who will criticize all of them. This controversy has yet to come to a satisfactory conclusion.

3. BMO SAMPLING PROCEDURES

The air samples for the ice nucleus concentration measurements were taken from 20 ft. above the ground at the BMO. This was made possible by means of a section of 2 in. i.d. plastic pipe. A blower motor on the bottom of the pipe kept air flowing through the pipe continuously. All three ice nucleus detection instruments were connected to the sample air intake above the blower by means of 3/8 in. i.d. copper tubing. All the instruments were located in one room of the BMO.

Operation of the three measurement systems was almost always accomplished by one of three scientists, and occasionally by a technician under the immediate supervision of a scientist. The scientists were all very familiar with the equipment prior to utilizing it in the field. Moreover, considerable effort was made to insure that the same operating techniques were used by all personnel.

The NCAR counter was operated at a chamber temperature of -20C. The counting rate was continuously recorded on chart paper upon which time checks were frequently made. Checks were occasionally made to make sure that the NCAR counter was functioning properly and some slight adjustments were sometimes necessary. Little else was normally required in the operation of this instrument.

The ice nucleus concentrations from the NCAR counter were adjusted by a multiplicative factor of 10. This is somewhat higher than the factor of 8 suggested by Langer and Weickmann (1971) to account for losses to the bottom of the chamber. The factor of 10 was used merely for convenience as the slight error introduced is negligible for the present purposes.

The Bigg-Warner expansion chamber was operated at a wall temperature of -10C and pressurized such that a temperature drop of 10C was achieved upon expansion. The nucleation temperature should have been, therefore, -20C. Sample air was drawn through the chamber at the rate of 10 ℓ min $^{-1}$ for at least 3 min before taking an observation. After this, the air sample pump was turned off, and the chamber was pressurized. The air in the chamber was allowed to come to thermal and moisture equilibrium for between 2 and 3 min. Then the pressure in the chamber was abruptly released, and the crystals were allowed to grow for up to several minutes before being counted. Counting commenced as soon as an appreciable fraction of the sampling tray was covered by ice, but before significant crystal merging occurred. After counting, the sugar solution was heated and the walls wiped with glycerin in preparation for the next sample.

The millipore filter sampler normally drew air through the filters at a rate of 5 ℓ min^{-1}. The air passed through the filter before entering the pump to prevent contamination. The duration of the sample varied from about one minute when it was suspected that the ice nucleus concentration was high, to about one hour when it was believed that the concentration was low. The estimate of the concentration was usually made on the basis of the concentrations measured by the NCAR counter. The 37 mm diameter filters, which were kept in closed plastic holders prior to exposure, were replaced in the plastic holders after exposure and were sent to NCAR where they were developed at a temperature of -20C.

Much of the time, all three of these methods were used simultaneously so that a comparison of the results obtained from each method was possible. The NCAR counter was used much more than the other two methods, largely due to convenience in that it required very little attention.

4. COMPARISONS OF BMO OBSERVATIONS

Comparisons were made of the values of ice nucleus concentrations obtained by means of the three methods described above. The results obtained from simultaneous measurements are shown in Figures 2, 3 and 4. Data obtained when no seeding material had been produced for at least 6 hours are indicated on the figures as from nonseeded periods. The

remaining data were considered to be from seeded periods, even if it was strongly suspected that the nuclei were not reaching the BMO during some of these times.

From these figures, it is immediately obvious that a given measurement by any one technique may be virtually unrelated to measurements made by either of the other two methods. It should be noted that there was a bias in the comparison between the NCAR counter and the Bigg-Warner chamber. This bias stemmed from the fact that at times when there was agreement to within about an order of magnitude between the results obtained with these two methods, more observations were made than at times when the agreement was poorer. In the latter case, the measurements were usually interrupted and attempts were made to locate any malfunctions in the equipment. The net result was that some points that would normally have fallen in the upper left or lower right portion of Figure 2 were omitted due to interruption of the measurements.

It is interesting to note that, in the mean, the concentration of ice nuclei as measured by the Bigg-Warner chamber was similar to the concentration derived from the NCAR counter measurements. The ice nucleus concentrations derived from the millipore filter method, however, tended to be lower than either of the other two methods by 1 to 2 orders of magnitude. It was suspected during the field season that many of the nuclei might have been penetrating the filters. However, changing from 0.45 μm to 0.22 μm filters seemed to make little or no difference in the magnitudes. Later laboratory tests, using ice nuclei from the same silver iodide generators used in the field, showed that very little penetration into the filters occurred even when 0.80 μm filters were used. However, it is possible that even slight penetration results in the nuclei being covered during the process of filling the filter with melted petroleum jelly.

In general, more confidence was placed in the performance of the NCAR counter than the performance of either of the other two methods by those working with ice nucleus detection at the BMO. This confidence stemmed largely from the fact that the NCAR counter would often register a substantial increase (1 or 2 orders of magnitude) in the number of ice nuclei at the BMO about 1/2 to 1 hour after the silver iodide generators were turned on at the seeding sites. Typically, only very slight increases if any at all were observed by the Bigg-Warner millipore methods. Such increases in the NCAR counter measurements were not observed at other times.

Further support for NCAR counter measurements resulted from airborne plume tracing investigations discussed by Super et al.(1972). Vertical cross sections of the seeding plume and measured winds were used to calculate the total ice nuclei crossing the Main Ridge per unit time on three separate occasions. These values were in good agreement with the AgI generator output as determined by calibration in the Colorado State University isothermal chamber.

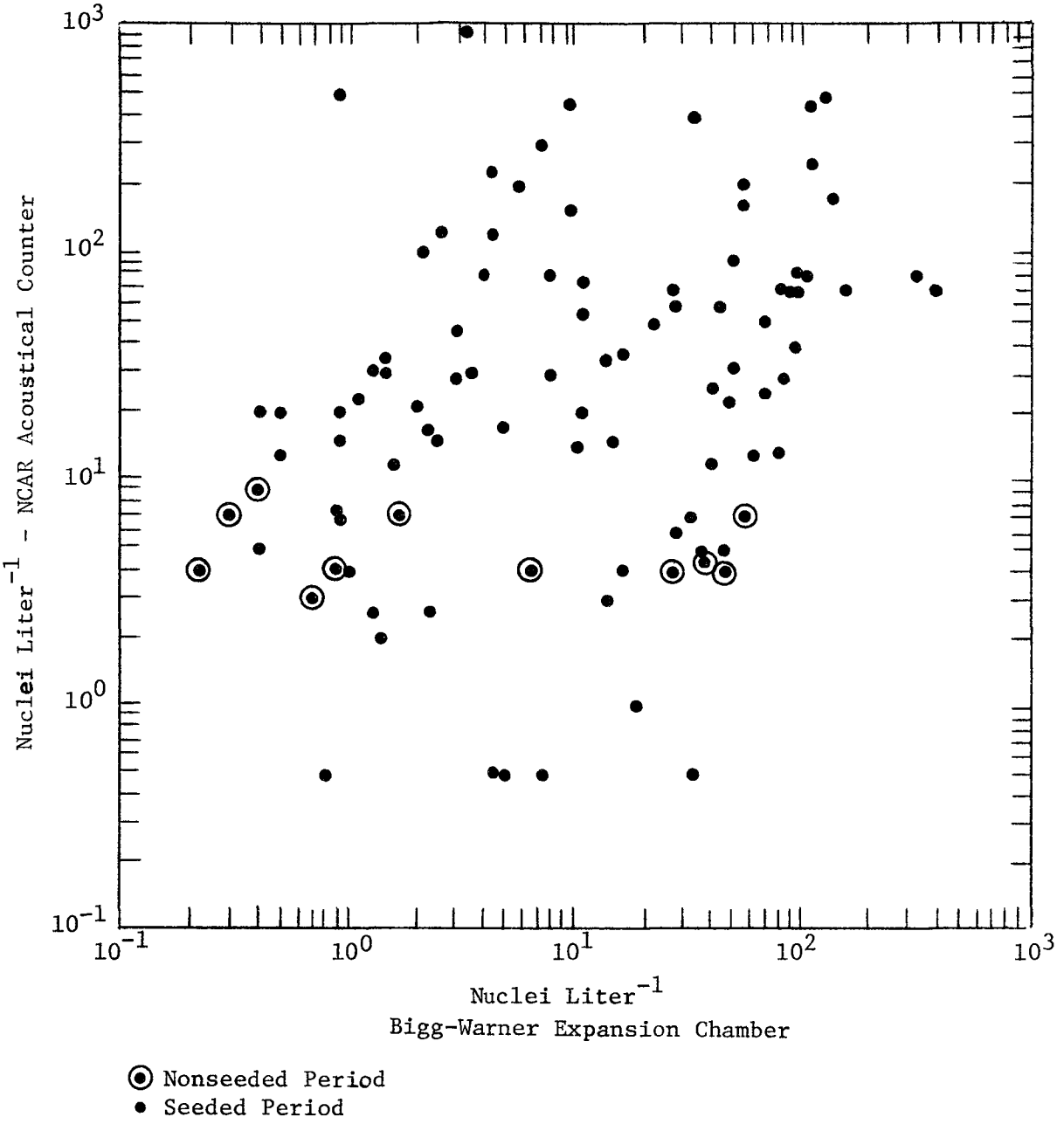


Figure 2.

Comparison of the ice nucleus concentrations at -20C as determined from the Bigg-Warner rapid expansion chamber and the NCAR acoustical counter. Measurements were taken at the BMO during the 1971-72 field season.

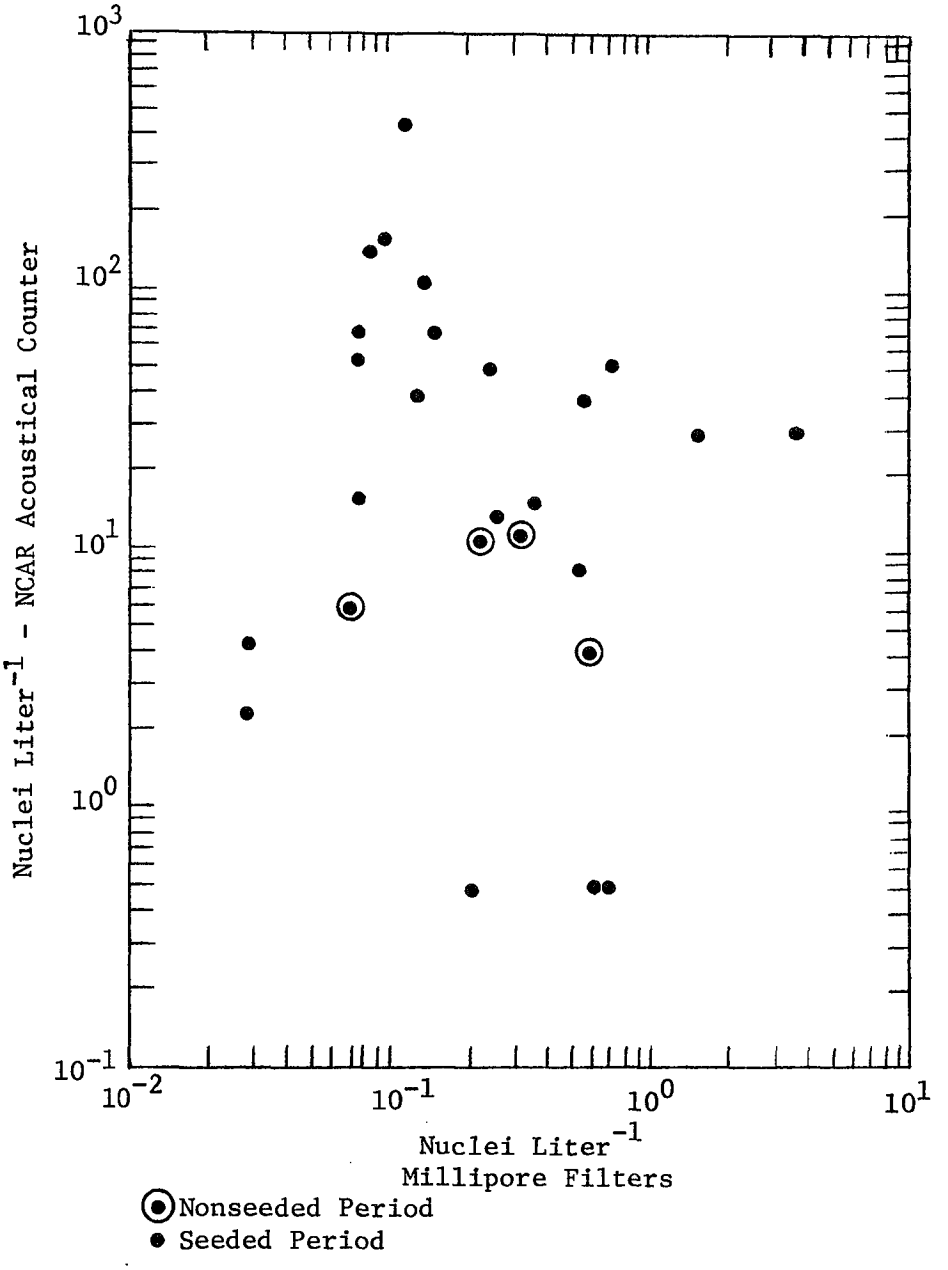


Figure 3.

Comparison of ice nucleus concentrations at -20C as determined from the NCAR acoustical counter and from the millipore filter technique. Measurements were taken at the BMO during the 1971-72 field season.

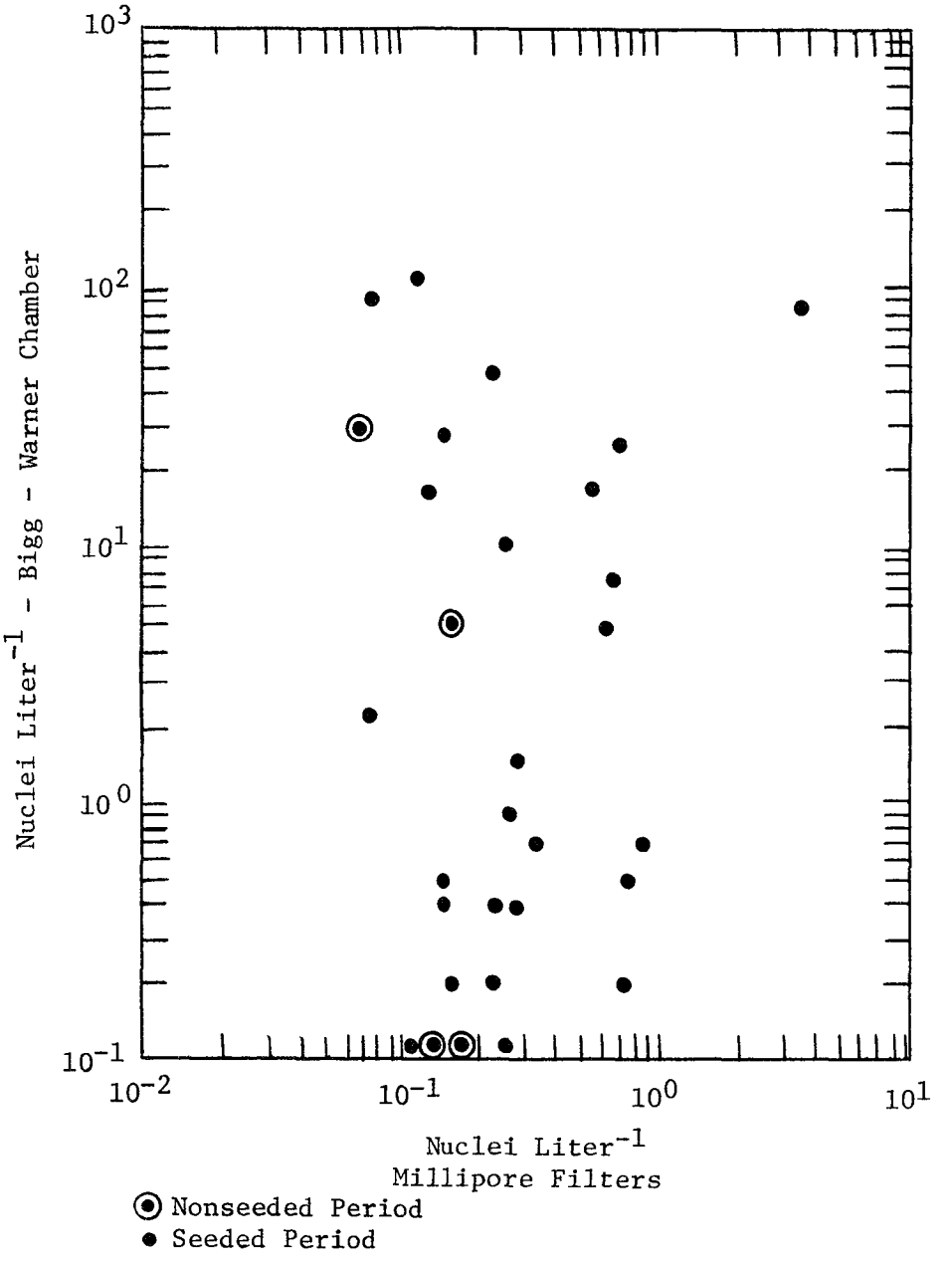


Figure 4.

Comparison of ice nucleus concentrations at -20C as determined from the Bigg-Warner rapid expansion chamber and from the millipore filter technique. Measurements were taken at the BMO during the 1971-72 field season.

5. COMPARISONS OF AIRBORNE MEASUREMENTS

Several comparisons between an airborne NCAR acoustical counter and the millipore filter method were made with measurements taken over the Main Ridge at elevations ranging from 8,500 to 11,000 ft MSL during March 1971. Filters were exposed to a 3.5 ℓmin^{-1} flow for periods of from 1.5 to 5.0 min. The filter pore size was 0.22 μm in all cases. Sample air was drawn off the same intake tube used for the NCAR counter. All airborne NCAR ice nucleus concentrations were increased by a factor of 10 as suggested by Langer and Weickmann (1971) when using an elbow with the sensor.

The resulting data are shown on Figure 5. It can be seen that considerable scatter of data points again existed, and that, with a single exception, concentrations measured by the NCAR counter were higher than those measured by the millipore filter. However, both the relative and absolute agreement was generally closer than found at the BMO as shown on Figure 3. A concentration greater than one nucleus liter $^{-1}$ was infrequently found from filters exposed at the BMO while concentrations ranged from 3 to 200 nuclei $liter^{-1}$ for the airborne filter samples. Yet, the concentrations measured by the NCAR counters had generally similar ranges for the BMO and airborne samples.

The most recent comparison between NCAR counter and millipore filter ice nucleus concentrations was made during the summer of 1972. The same airborne NCAR counter and millipore filter techniques were used to sample ground-released plumes of AgI near Rapelje in south central Montana. The generators and silver iodide solutions were the same as in use when previous comparisons were made.

Samples were taken between 1,000 and 9,000 ft above ground, and at distances from the generators ranging from 2 to 25 mi. The 0.22 μm millipore filters were exposed to a 4 ℓmin^{-1} airflow for periods ranging from 2 to 15 min. The silver iodide collected on most samples was generally exposed to direct sunlight as only a few scattered cumulus were present. However, a thunderstorm moved through the area late in the sampling period and some samples were collected under a cirrus overcast, and still later a few were taken in rainfall.

Figure 6 shows a comparison of the ice nucleus concentrations measured by the two methods. While the sample size was limited, differences in sky cover did not obviously influence the relationship between the two techniques. It is worthy of note that the scatter in Figure 6 is substantially less than that in Figure 3 or Figure 5. It should also be noted that the absolute agreement between the two methods is quite good in Figure 6.

Conditions differed from prior comparisons in that the seeding material was exposed to warmer air with higher specific humidity. Also, the turbidity of the air was substantially greater due to bare underlying ground and considerable convective activity. One can only speculate on

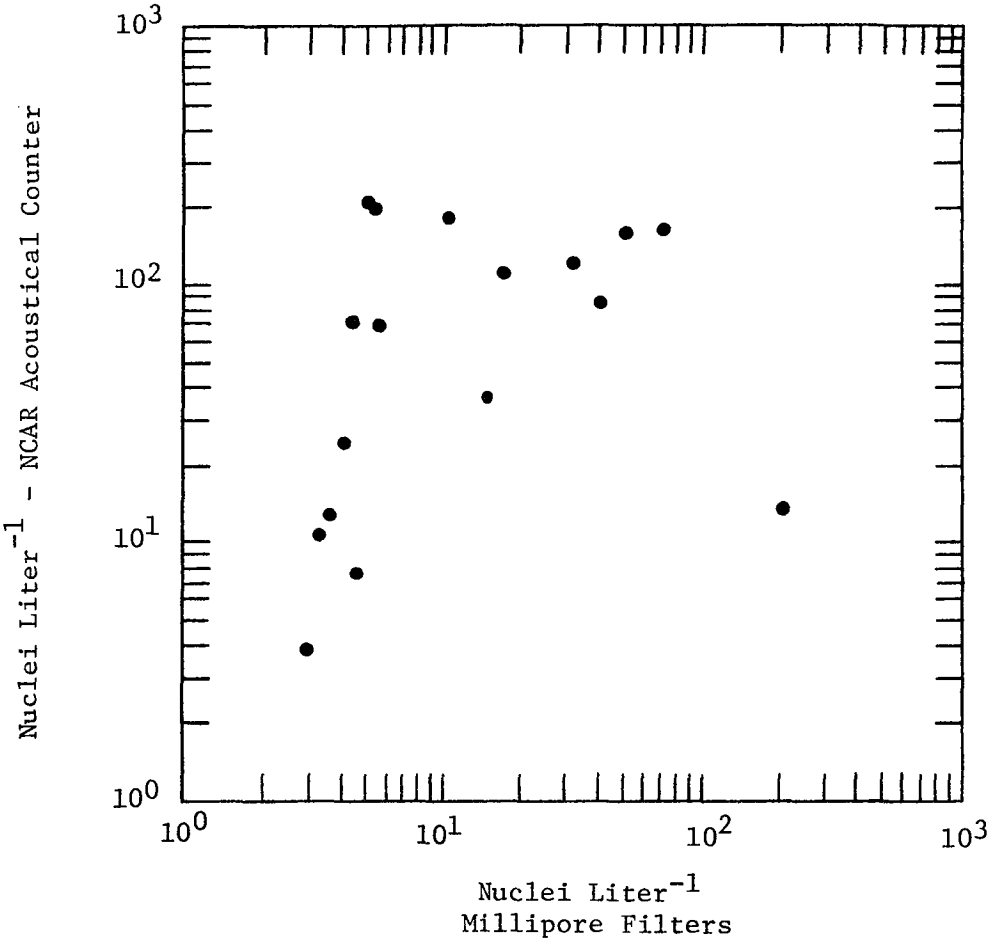


Figure 5.

Comparison of ice nucleus concentrations at -20C as determined from the NCAR acoustical counter and from the millipore filter technique. Airborne measurements over the Bridger Range in March 1971.

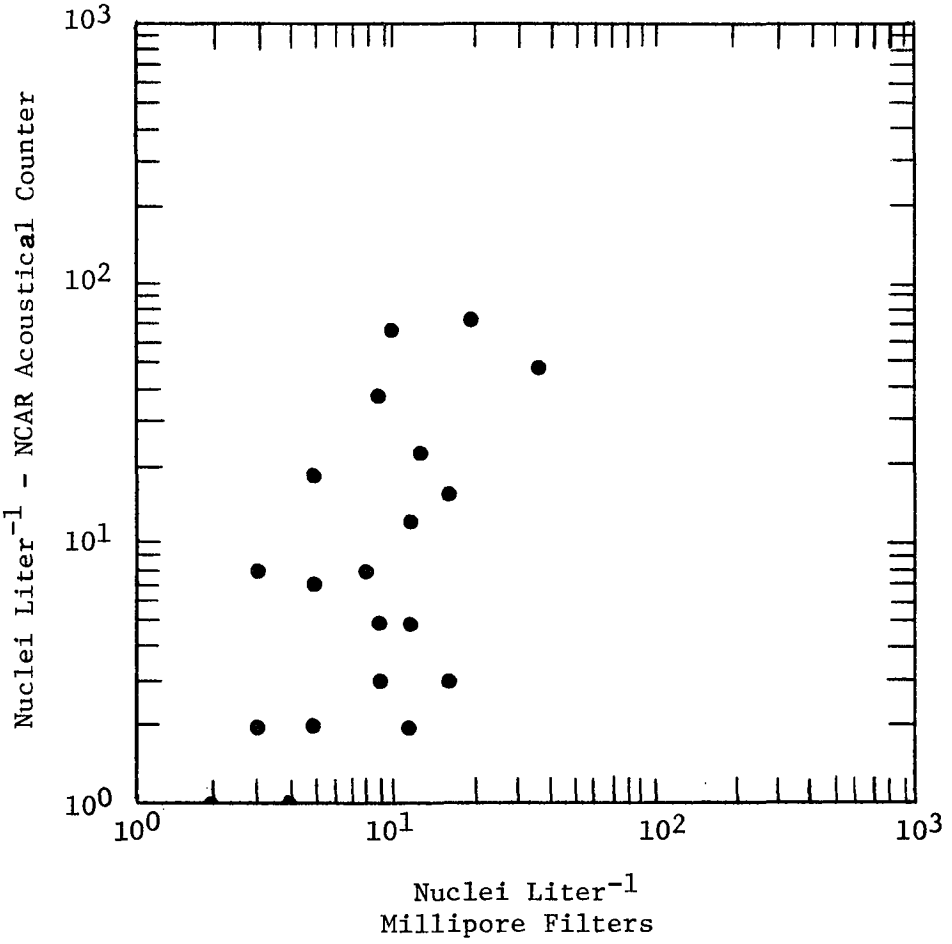


Figure 6.

Comparison of ice nucleus concentrations at -20C as determined from the NCAR acoustical counter and from the millipore filter technique. Airborne measurements taken near Rapelje, Montana, on 16 August 1972.

the manner in which these differences may have influenced nucleation in the NCAR counter or in the millipore filters.

6. DISCUSSION

From the comparisons presented here, it is obvious that the agreement between the NCAR counter and the millipore filter method was much better in the sets of airborne data than it was among the data taken at the BMO. The reason for the better agreement among the airborne data is not obvious. Laboratory comparisons made between the airborne NCAR counter and the NCAR counter used at the BMO showed excellent agreement. The method of analysis used by Dr. G. Langer (personal communication) did not change significantly for the three sets of millipore filters. Thus, it would appear that the poorer agreement found at the BMO may be related to the fact that the nuclei usually traveled several miles in cloud and snowfall before being sampled. Airborne samples over the Bridger Range were taken below cloud base during nonprecipitating periods. Most measurements obtained during the summer in south central Montana were made under clear skies.

The fact that better absolute agreement was found to exist between the NCAR and millipore techniques during the summer airborne measurements than during the winter airborne measurements suggests that the distance the nuclei traveled was relatively unimportant as the summer measurements were made from 2 to 25 mi downwind of the AgI generators. It also suggests that ambient temperatures, or atmospheric turbidity may influence one method more than another.

It can be hypothesized that the more active ice nuclei were utilized in nucleation prior to reaching the BMO, and that a higher proportion of the less active nuclei remaining were activated by the NCAR counter than by the millipore technique. Another hypothesis is that the nuclei, in passing through the orographic cloud, became less susceptible to detection by means of the millipore filter technique. While there is no factual basis for either of these hypotheses at this time, either one would explain the observed behavior of the ice nuclei comparisons. There may be other hypotheses that would explain this behavior as well. However, it seems obvious that the NCAR counter and the millipore filter technique are sensitive to different things. Which more closely represents conditions in a real cloud remains a matter for future research.

It is obvious that one cannot definitely determine from the data presented herein whether any of the three ice nucleus measurement techniques employed produced valid data. The very poor agreement that was found to exist among the three methods used at the BMO suggests that one must use considerable caution in interpreting the results of ice nucleus concentration measurements. It would appear from these comparisons that each of these methods is sensitive to different characteristics of the ice nuclei. Considerable additional work will be required to determine what these different ice nucleus characteristics are and

which of these are important in natural clouds. In the absence of this information, the authors tend to believe that the NCAR acoustical counter was superior to the other two instruments employed in detecting AgI nuclei for reasons previously discussed.

- - - - -

ACKNOWLEDGMENTS

This research was sponsored by the Division of Atmospheric Water Resources Management, Bureau of Reclamation, U.S. Department of the Interior, under contract 14-06-D-6798. The authors wish to thank Dr. G. Langer of NCAR for his advice and assistance, and Mr. J. McPartland who aided in taking many of the measurements reported.

- - - - -

REFERENCES

Bigg, E. K., 1971: Report on the Ice Nucleus Workshop Fort Collins, August 1970. The Second International Workshop on Condensation and Ice Nuclei. Dept. of Atmospheric Science, Colorado State University, Fort Collins, Colorado, 97-105.

Grant, L. O., ed., 1971: The Second International Workshop on Condensation and Ice Nuclei, Fort Collins, Colorado. Dept. of Atmospheric Science, Colorado State University, Fort Collins, Colorado, 149 pp.

Kline, D. B. and G. W. Brier, 1961: Some experiments on the measurement of natural ice nuclei. Monthly Wea. Review, 89 (8) 263-272.

Langer, G., 1971: Comments regarding operation of the NCAR ice nucleus counter. J. Atmos. Sci., 28, 1074-1076.

_____, J. Rosinski, and C. Edwards, 1967: A continuous ice nucleus counter and its application to tracking in the troposphere, J. Appl. Meteor., 6, 114-125.

_____, and J. Weickmann, 1971: Detailed evaluation of the NCAR ice nucleus counter--Initial Report. Proceedings of the International Conference on Weather Modification, Canberra, Australia, Sept. 6-11, 1971, 45-50.

Stevenson, Catherine M., 1968: An improved millipore filter technique for reassuring the concentrations of freezing nuclei in the atmosphere. QJRMS, 94 (399), 35-43.

Super, A. B., C. A. Grainger, J. T. McPartland, V. L. Mitchell, and R. H. Yaw, 1972: Interim Final Report, December 1972, Atmospheric Water Resources Program, Bureau of Reclamation, Denver, Colorado, Contract No. 14-06-D-6798, 420 pp.

United States Weather Bureau, 1959: Provisional operating instructions for ice nuclei counter (experimental Bigg-Warner type). Washington, D. C., October, 17 pp.

- - - - -

RAW AND IODINE TREATED AUTOMOBILE EXHAUST AS A SOURCE OF ICE NUCLEI

Lewis O. Grant and Myron L. Corrin

Colorado State University
Fort Collins, Colorado

A. INTRODUCTION

Inadvertent modification of weather and climate by human activities is appropriately receiving increasing attention. Landsberg (197) has recently reviewed and evaluated various processes which should be considered. The following types of changes may occur from alterations in various atmospheric processes: (1) radiational changes due to changes in sky cover from clouds and pollutants, (2) changes in atmospheric heating due to changes in atmospheric constituents, such as CO_2, and (3) changes in the colloidal stability of clouds (and precipitating efficiency) from inadvertent changes in the characteristics of atmospheric nuclei. Investigation of these various processes are in progress by various research groups.

The availability of condensation nuclei from pollutants for the formation of liquid droplets from water vapor can result in many more, but smaller cloud droplets. This additional supply of condensation nuclei greatly increases cloud microstability and can impede the formation of precipitation in some clouds. Inadvertent weather modification by this process is being considered and evaluated by several research groups. The role that atmospheric pollutants may play in changing the availability and characteristics of atmospheric ice forming nuclei has received less attention. Some investigators have reported increased concentrations of ice nuclei downwind of some industrial sources. Schaefer (1966) and Morgan and Alee (1967, 1968) have specifically suggested the possibility that lead emitted from automobile exhaust may be a major source of inadvertent ice nuclei. Lead iodide is clearly a very effective ice nucleant. The production of this ice nucleant would, as pointed out by Schaefer, require an additional source of iodine which itself is very rare in the free atmosphere. Morgan and Allee (1968) and Montefinale et.al. (1971) suggest further the possibility of using the lead from combustion sources, combined with artifically supplied iodine vapor, as a purposeful source of ice nuclei. Montefinale et.al. have designed an evaporator for producing substantial quantities of iodine to react with lead pollutants for purposes of intentional weather control. They have utilized the evaporator to react with pollutants over the city of Turin, Italy for purposes of intentional hail suppression.

B. PURPOSE OF RESEARCH

The general purpose of a portion of an investigation of environmental contamination caused by lead is to evaluate the implication of the ice activation characteristics of exhaust from automobiles and other lead emitting

sources. The overall objective includes an interpretation of the effect of inadvertently produced ice nuclei on atmospheric cloud systems and precipitation. Specific objectives include: (1) the description of the temperature activation characteristics of ice nuclei in fresh and stored automobile exhaust, (2) the description of the temperature activation characteristics of ice nuclei in fresh and stored automobile exhaust when exposed to iodine, (3) the description of the temperature activation characteristics of the specific lead compounds actually present in automobile exhaust, (4) the description of the ice activation characteristics of other constituents in automobile exhaust, (5) the verification and interpretation of the significance of the above laboratory findings over specific polluted sources, and (6) the interpretation of the significance of the ice nucleating characteristics of atmospheric pollutants on clouds and precipitation.

The interdisciplinary nature of this program makes possible a broad attack which involes (1) nucleation tests in laboratory cloud chambers, (2) chemical analyses and interpretation, (3) field sampling, and (4) evaluation of the implications of the findings by the use of numerical models of cloud and precipitation processes.

C. PROCEDURES AND EQUIPMENT

1. Laboratory Studies

The laboratory tests are being conducted in the CSU Isothermal Cloud Chamber. This cloud chamber has been described in the report of the International Workshop on Condensation and Ice Nuclei, Slusher et.al, (1971). The isothermal cloud chamber has a 1.4 cubic meter volume into which a supercooled cloud is introduced. All points in the chamber are at a temperature within plus or minus 0.5° of the desired testing temperature throughout the useable temperature range of the chamber, -5° to -25°C. The liquid water content within the chamber may be controlled between 0 and 1.5 grams per cubic meter. Modifications in the chamber since the International Workshop provide for the introduction of the cloud from the top of the chamber at the same temperature at which the chamber is operating. This almost completely eliminates supersaturations that might be created by a differential in temperature between the freshly introduced cloud and the chamber environment. Further, since the chamber is humidified by droplet settling, internal convection is largely eliminated.

Samples of automobile exhaust, and of each of the individual constituents of automobile exhaust, are introduced into the cloud chamber for activation as ice nuclei. Additional observatons are made during which the samples are exposed to iodine and other vapors. Cloud chamber temperatures are varied to obtain the temperature activation characteristics of the varous pollutants. Initial testing was carried out using exhaust from employee automobiles. As the work progressed the requirement for more precise replication of the exhaust samples and for the elimination of possible lead contamination in the tests with non-leaded gasoline became apparent. Subsequent testing has been carried out using two identical five horsepower, four cycle single cylinder, Briggs and Stratton engines. These engines were purchased new. Tests with leaded gasoline have been run in one of these engines while all

tests with non-lead gasoline have been made with the other. To insure that no residue from factory tests contaminated the fuel, each engine was thoroughly cleaned prior to its initial use. Controls were incorporated to insure that the running characteristics of these two engines were similar during all tests. This was done by adding an identical load on each engine. This sytem consits of a water driven pump connected to a reservoir by pipes. A loading control valve on the pressure gauge is attached to each engine. This common loading system includes a common throttle and shut off control for the respective units.

Further steps have been taken to control the temperature and the moisture content of the exhaust samples. Uniform cooling of the exhaust is accomplished by the incorporation of four foot six inch tubes to the exhaust pipe. These tubes transmit the heat from the exhaust to the environment so that the samples are systematically cooled and controlled for injection into the cloud chamber. Two systems have been employed for the removal of water vapor from the exhaust since this vapor could produce local supersaturations as the sample is introduced into the cloud chamber. With system one, moisture is lowered to a dew point of $-20^{o}C$ by passing the sample through a molecular sieve 5A. With the second system a cold trap is used. With this system, exhaust is passed through a cold trap immersed in a solution of dry ice in acetone with a temperature near $-75^{o}C$. The potential for losing portions of the exhaust pollutant along with the removal of water exists with both systems. Attempts have been made to evaluate these losses. Water condensed in the cold trap has been analyzed for the presence of lead which may have diffused to the walls along with the water vapor. These analyses show that less than 1% (.57%) of the lead that would be emitted in the exhaust was collected in the wall condensate. Evaluation of the losses in the molecular sieve have been limited to comparative tests of the nucleating characteristics of the exhaust after short and prolonged use of the molecular sieve. Only minor differences in the nucleating characteristics of the exhaust materials are observed with different exposure times. Further, comparable cloud chamber results are obtained with sample dehumidification by either the cold trap or sieve desiccating systems.

2. Field Studies

The Colorado State University Aero-Commander has been instrumented for the field sampling. Ice forming nuclei are continuously monitored during flight with an NCAR acoustical counter, Langer (1971). Further, observations are made at approximately 10 minute intervals with a Bigg-Warner expansion counter, used both as an expansion counter and as a diffusion chamber, Reinking and Grant (1971), and with millipore filters collected for laboratory analyses in a thermal diffusion chamber, Gagin (1971). Flight patterns have been above Interstate 25 from Fort Collins south over the city of Denver at elevations from 5500 feet mean sea level to 11,000 feet mean sea level (ground surface is generally around 5,000 mean sea level). Comparisons are being made of the location, temperature activation characteristics, and the concentration of the pollutants. Separate sampling will be used to describe the amounts of lead in the pollutants encountered.

D. EXPERIMENTAL RESULTS

This inadvertent weather modification investigation is still in progress. Important results are now becoming available from the laboratory studies, both for the nucleating characteristics of automobile exhaust and for the nucleating characteristics of the individual gasoline constituents. The field studies are in a preliminary stage. This section summarizes the primary results now available.

1. Automobile Exhaust as an Ice Nucleant

a. Raw Exhaust

Nearly all materials or compounds will serve as ice forming nuclei at temperatures warmer than the homogeneous freezing temperature near -40°C. Schaefer (1951) has shown the temperature activation for a number of materials in terms of a threshold temperature at which the first particles become active and in terms of a complete activation temperature at which nearly all particles become active. He shows threshold temperatures for silver iodide at about -4°C and for various soil particles at about -9°C to -20°C. Except for silver iodide, none of the various materials shown by Schaefer show extensive activity until temperatures are below at least -20°C. Our tests show that the ice nucleating characteristics of raw automobile exhaust are clearly most comparable to the least efficient materials shown by Schaefer. These tests show that automobile exhaust has a threshold temperature near -18°C and becomes increasingly effective as an ice nucleant as cloud temperature decreases to around -28°C. This is shown in Figure 1 which shows the average temperature activation spectrum for two cars in comparison to a reference sample of clean air and with a typical spectrum (shown as "World average") for natural ice nuclei. It can be seen that at temperatures near -18°C the concentration of ice nuclei activated is not increased over concentrations observed in the clean reference sample and is near (actually lower) than the world wide average reported for this temperature. It can also be noted, at still colder temperatures, that the automobile exhaust, relative to the reference sample, becomes increasingly effective as an ice nucleant. At a temperature of -28°C the automobile exhaust is from about 45 (car 1) to around 200 (car 2) times as effective as the reference sample. The gasoline used in the above tests was commercially available, regular gasoline containing lead tetraethyl and scavengers.

These results are not substantially affected by the presence of absence of lead in the gasoline. In comparative tests of leaded and lead free gas, the particles activated for the respective samples were within a factor of two at temperatures ranging from -18°C to -24°C. These tests have been run separately with automobile exhaust, with exhaust from a two-cylinder gasoline engine and with exhaust from the four-cycle Briggs and Stratton engine. Curves A and B of Figure 2 show the concentrations of ice particles activated above background, respectively for leaded and lead free gasoline for tests run with the Briggs and Stratton paired engines. These are presented in terms of the ratio of concentration of ice crystals observed in the cloud chamber to a threshold concentration of unity. The close parallel of these two curves is readily apparent. The leaded gasoline used in these tests was regular Amco gasoline (approximately 600 ppm Pb). The "lead free" gasoline was Amoco Pb-free gasoline (analyzed at CSU to be $\leq$.1 ppm Pb).

AVERAGE ACTIVATION SPECTRUM OF ICE NUCLEI
FOR AUTO EXHAUST FROM TWO CARS
FORT COLLINS, COLORADO DECEMBER 1970

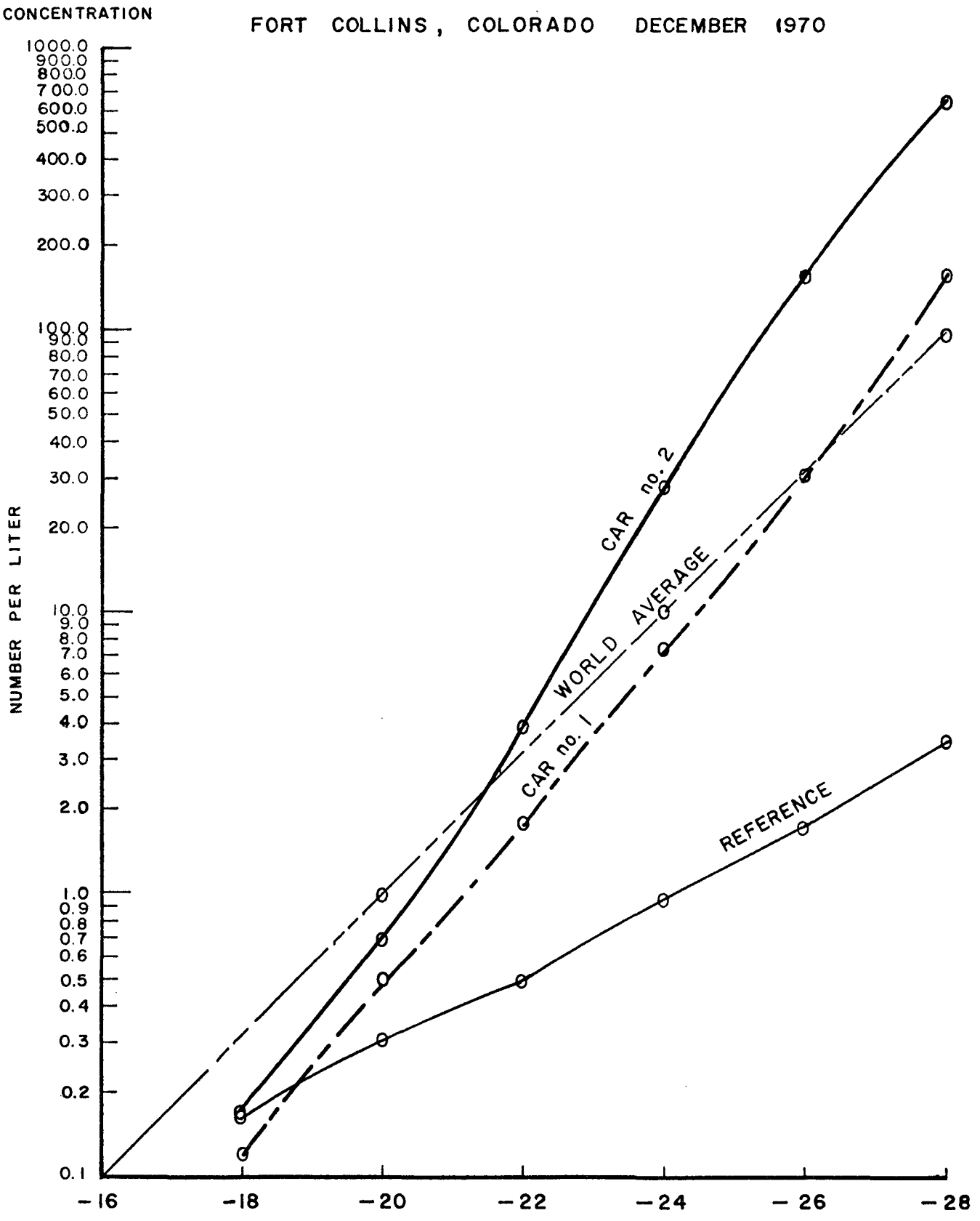


Figure 1.

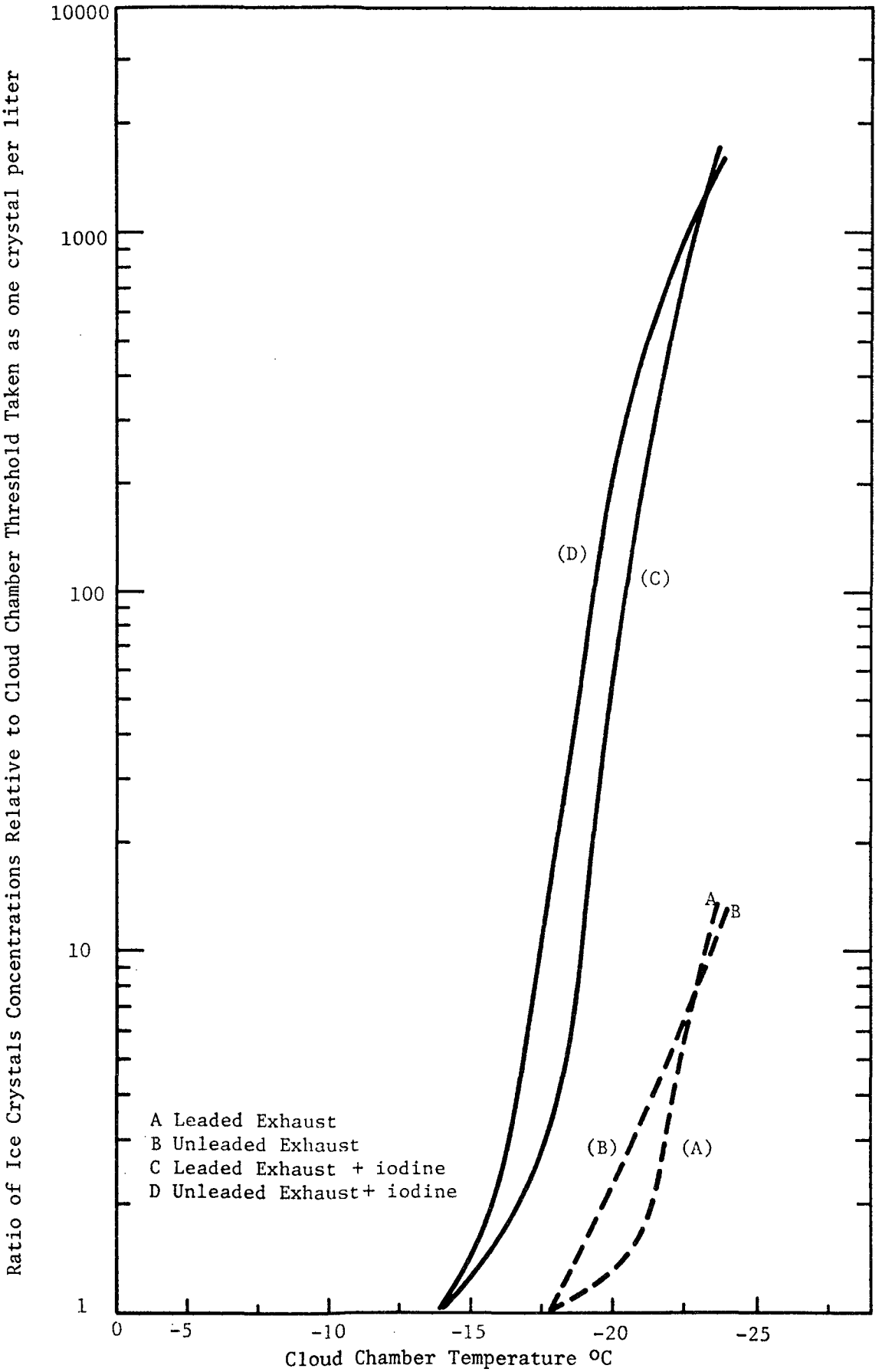


Figure 2.

Ration of Concentration of Ice Crystals Fromed From Raw and Iodine Treated Auto Exhaust Produced from Leaded and Lead Free Gasoline

b. Raw Exhaust Exposed to Iodine Vapor

As has been reported by other investigators, the concentration of ice forming nuclei is greatly increased when the automobile exhaust is exposed to iodine vapor. Again these comparisons have been made using auto-exhaust, a two-cycle gasoline engine and the paired Briggs and Stratton engines.

Curves C and D of Figure 2 show the comparative values, respectively, for the leaded and "lead free" gasoline when exposed to iodine vapor for samples obtained from the Briggs and Stratton paired engines. It is readily apparent that, when iodine vapor is supplied, the threshold temperature is increased by about 5°C and that, depending on temperature, the concentration of ice forming particle is increased above chamber threshold by a factor of from 3 to over 100. It can further be noted that, while the increase occurs with both the leaded and non-leaded gasoline, the increase actually was the greatest for the "lead free" gasoline through most of the temperature range. The iodine concentration in these samples was .0023 gm per liter of exhaust. In terms of a reasonable estimate of the lead in the exhaust of regular gasoline, the stochiometric ratio of iodine to lead was about 1000.

Schaefer in private conversations has suggested that the considerable increase in particles activated in the non-leaded gas may have formed from a reaction with the minute, but still present, concentrations of lead in the non-leaded gasoline. To evaluate this possibility, the average size of the lead particles present has been calculated from considerations of the numbers of particles activated and the amount of lead present (approximately .12u gm/liter). Calculations show that the mean diameter of the particles would be around or less than 100A. From nucleation consideration, particles of this size could not be expected to serve as ice nuclei in the manner observed.

2. Gasoline Consitituents as Ice Nucleants

Schaefer (1966) and Morgan et.al. (1967, 1968) and Montefinale (1971) have assumed that the large numbers of effective ice nuclei formed when automobile exhaust is exposed to iodine results from a reaction with lead. The results reported above raise questions regarding this assumption since the ice nucleating efficiency of exhaust, when exposed to iodine, for "lead free" fuel (burned in a clean engine) is at least as high as when leaded fuel is used. This seeming contradiction is being explored further by testing the ice forming characteristics of each of the constituents present in commercially available gasoline.

a. Raw Constituents

As with raw automobile exhaust, the nucleating efficiency of each of the individual raw constituents is also low. Tests with the following

constituents show no substantial increase in nucleating efficiency at temperatures around -20°C.

Isooctane (the basic fuel tested)

Lead Chlorobromide

Tetraethyl-lead

Isooctane plus lead tetraethyl

These exhaust samples were all obtained from the Briggs and Stratton engines except for the lead chlorobromide. Since lead chlorobromide is believed to be the basic lead compounds in automobile exhaust, a test sample of this compound was prepared. Its nucleating efficiency is being tested with the use of an aerosol spray. PbClBr is dissolved in water at a prescribed concentration. An ultrasonic nebulizer is then used to produce a fine cloud which is then mixed with dry air to evaporate the liquid and leave a PbClBr aerosol. The sample containing this aerosol is then injected into the cloud chamber.

b. Raw Constituents Exposed to Iodine

(1) Isooctane - a slight increase in the concentration of ice particles occurs when isooctane is exposed to iodine vapor. The increase is of the same order of magnitude as occurs when iodine alone is injected into the cloud chamber (probably from reaction with background pollutants). Further tests will be required to evaluate whether the slight increase with iso-octane exposure to iodine is significant.

(2) Lead chlorobromide - Again as with the isooctane, the increase in the concentration of ice particles when PbCLBr is exposed to I2 is above chamber background but is comparable to the increase caused by iodine alone. The increase is somewhat higher (perhaps by a factor of 2) than with isooctane, and further tests will be required to define the detailed nucleation effect when lead chlorobromide is exposed to iodine. Clearly, no major increase in nucleating efficiency was observed with the exposure of lead chlorobromide to iodine. Since this is the primary lead compound in automobile exhaust, this result appears to be consistent with the results which show only similar increases in ice particle production when auto-exhaust for both leaded and "lead free" gasoline is exposed to iodine. This, appears to be a reasonable result if the lead compound that is effective as an ice nucleant is PbI_2, since the Cl and Br bonding to lead is chemically sufficiently stable to preclude its displacement by iodine for the formation of PbI_2. The free energy change for the reaction

$$PbClBr(s) + I_2\ (g) \rightarrow PbI_2(s) + 1/2Cl_2\ (g) + 1/2\ Br_2\ (g)$$

may be calculated from standard free energies of formation

(1) $Pb(s) + 1/2\ Cl_2(g) + 1/2\ Br_2(1) \rightarrow PbClBr(s)\ \Delta G^o = -68.0Kcal$

(2) $Pb(s) + I_2(g) \rightarrow PbI_2(s)\ \Delta G^o = -41.5Kcal$

and

$$PbClBr(s) + I_2(g) \rightarrow PbI_2(s) + 1/2Cl_2(g) + 1/2Br_2(l) \quad \Delta G^o = +26.5Kcal$$

For $Br_2(l) \rightarrow Br_2(g)$ $\Delta G=o$ at the vapor pressure of the liquid and thus

$$PbClBr(s) + I_2(g, p=1 \text{ atm}) \rightarrow PbI_2(s) + 1/2Cl_2(g, p=1 \text{ atm}) + 1/2Br_2(g, p=.3 \text{ atm})$$
$$\Delta G^o = 26.5Kcal$$

For the process

$$1/2Br_2(g, p=0.3 \text{ atm}) \rightarrow 1/2Br_2(g, p=1 \text{ atm}) \quad \Delta G = 1/2RT1n\ 1/.3 = 0.36Kcal$$

Thus

$$PbClBr(s) + I_2(g) \rightarrow PbI_2(s) + 1/2Cl_2(g) + 1/2Br_2(g) \quad \Delta G^o = 26.9Kcal$$

The equilibrium constant for the reaction

$$K_{eq} = e^{-\Delta G^o/RT} = 10^{-20}$$

and the reaction is highly improbable.

(3) Lead iodide - As is well known, PbI_2 is a very effective ice nucleant. PbI_2 has been tested for a comparison of its nucleating efficiency with that for PbClBr. PbI_2 has been produced from (1) the burning of an isooctane tetraethyl lead mixture (no scavenger) in the gasoline engines, (2) the mixing of the tetra-ethyl lead and iodine vapors, and (3) the spraying of PbI_2 prepared in the aerosol generator in a manner similar to that used for the PbClBr. In all cases large increases (10^2 to 10^3 above cloud chamber threshold) in concentrations of ice crystals have been observed. The concentrations observed represent a production of about 1×10^{12} particles/gmPbI_2 effective at -20^oC for both the aerosol generator and the gasoline engine.

3. Discussion of the Laboratory Testing

Techniques have now been developed for making comparative tests of leaded and non-lead gasolines under similar controlled condition with minimized contamination. While additional testing is required to establish refined values, it is clear that neither raw automobile exhaust or any of the individual constituents thus far tested, are effective ice nuclei at temperatures warmer than about -18^oC. Automobile exhaust becomes a progressively better nucleant at colder temperatures. The concentration of effective ice nuclei per liter of exhaust increase by about an order of magnitude for a decrease of every 3^o to 4^oC in temperature.

The ice activation characteristics of automobile exhaust is greatly enhanced by the addition of iodine vapor. Testing to date indicates that this is not from the formation of PbI_2 as has been postulated by previous investigations. First, chemical analyses show that the primary lead compound in automobile exhaust is PbClBr. Chemical equilibrium considerations show that I_2 cannot be expected to displace the ClBr to form PbI_2.

The low concentrations of ice crystals produced with the exposure of PbClBr to iodine, and the high concentrations of ice crystals formed from lead free gasoline are tentatively interpreted to indicate that (1) PbClBr, the primary lead compound in gasoline, is not a good ice nucleant and (2) that it is not a lead reaction with iodine in auto exhaust that produces the large numbers of ice nuclei observed when auto exhaust is exposed to iodine.

In addition to the refinement of present results, several basic questions still must be answered. The above results indicate that the ice nucleants are formed by the reaction of iodine with automobile exhaust. They indicate that this is not from lead present in the gasoline. The actual nucleant formation processes when automobile exhaust is exposed to iodine are now being considered. It does not appear that they are formed from an iodine reaction with the isooctane or with the lead. Reactions with the other gasoline additives are now being considered and tested.

Another consideration involves the effect of storage on the nucleating processes considered above. This is vital since exhaust products over polluted areas can exist, and interact with other pollutants, during extended periods of time. A large storage chamber is being prepared for storing exhaust and exhaust constituents. Samples will then be taken from this chamber for establishing nucleation changes with time. Further, field sampling is being started over polluted Interstate No. 25 and several cities to extend the laboratory findings to the atmosphere.

4. Field Studies

Analysis of preliminary field observations are still in progress. Emphasis is being placed on establishing the relationship between the ice nuclei counters being used in the field with the cloud chambers used for the laboratory analysis. Flights through areas with raw pollutants have, as found in the laboratory, shown, with some exceptions, low ice nuclei concentrations. Increases in concentrations have occurred when the samples were exposed to iodine vapor, although the increases have not been as spectacular as those obtained with raw automobile exhaust in the laboratory. Highest concentrations have been observed just north of Denver on the low elevation traverses (<1000' above the terrain) and well north of the Denver area on the higher traverses (up to 6000' above the terrain).

January 1973

- - - - - - -

ACKNOWLEDGEMENTS:

The assistance of Stan Brown, Ronald Rinehart, Dave Dahl, Jack Simmons, and Steve Vardiman in making the cloud chamber test is greatfully acknowledged. This research was supported by the National Science Foundation through the RANN Program on Environmental Systems and Resources Grant GI-34813X.

REFERENCES

Gagin, A., 1971: A Thermal Diffusion Chamber for Ice Nuclei Measurements. The Second International Workshop on Condensation and Ice Nuclei, Fort Collins, Colorado, pp.53-54.

Landsberg, H. E., 1970: Man-made Climatic Changes. Science 170: 1265-1274.

Langer, G., 1971: Lone-Cone NCAR Ice-Nucleus Counter. The Second International Workshop on Condensation and Ice Nuclei, Fort Collins, Colorado, pp. 46-48.

Montefinale, A. C., et al., 1971: An Evaporator of Iodine for Purposes of Weather Control. Pageoph, Vol. 91, pp. 211-217.

Morgan, G. M. Jr. and P. A. Allee, 1967: The Production of Potential Ice Nuclei by Gasoline Engines. Final Report, Contract E22-98-67N, E. Bollay Associates, 25 pp.

Morgan, G. M., Jr., and P. A. Allee, 1968: The Production of Potential Ice Nuclei by Gasoline Engines. Journal of Applied Meteorology Vol. 7, No. 2, pp. 241-246.

Reinking, R. F. and L. O. Grant, 1971: The Colorado State University Rapid-Expansion Ice Nucleus Counter. The Second International Workshop on Condensation and Ice Nuclei, Fort Collins, Colorado, pp. 71-75.

Schaefer, V. J., 1951: The Occurrence of Ice Crystal Nuclei in the Free Atmosphere. General Electric Research Laboratory, Final Report Project Cirrus, Report No. RL-566, pp. 180-203.

Schaefer, V. J., 1966: Ice Nuclei from Automobile Exhaust and Iodine Vapor. Science, 154: 1555-1557.

Slusher, T., 1971: CSU Isothermal Cloud Chamber. The Second International Workshop on Condensation and Ice Nuclei, Fort Collins, Colorado, pp. 60-61.

- - - - -

THE STIMULATION OF RAIN IN YUGOSLAVIA

Dr. Drazen Poje

Zagreb, Yugoslavia

1. INTRODUCTORY REMARKS

In the Yugoslav balance of energy, the production of electricity from hydroelectric plants has an important place: in the year 1971 these plants participated in the overall production of electric energy in Yugoslavia with 65.2%.

Owing to the fact that a large part of hydroelectric plants' power output depends heavily on the precipitation regime, it is understandable that more than ten years ago the artificial stimulation of rain over the catchment areas of certain hydroelectric plants was considered.

During recent years the fluctuations of precipitation amounts in the greater part of Yugoslavia have been extremely large. Long periods of droughts may cause extensive losses in power production and in that way lead to great economic losses. In the period 1969-1971 the reduction of electric current in the three greatest industrial regions of Croatia amounted to nearly 46000 Mwh.

Several years ago some Yugoslav hydroelectric plants financed research to find the climatic potential for stimulation of rain in two selected experimental regions of Yugoslavia.

In this report some basic results of this research, which was carried out by the Republic Hydrometeorological Institute of Croatia in Zagreb, will be presented as well as plans for recent investigations and future actions.

2. THE BASIC FEATURES OF EXPERIMENTAL REGIONS

As experimental regions, two areas in the southwest part of the Socialist Republic of Croatia were selected: the first one in Gorski Kotar and the second one in Lika, both situated in the vicinity of the Adriatic Sea.

Gorski Kotar is a karst plateau with an average altitude of 700 - 800 meters, richly forested and with numerous valleys. The area includes an important mountain range with peaks between 1200 and 1500 meters above sea level which causes uplift of moist air masses from the Adriatic sea and abundant precipitation. The total catchment area of the hydroelectric power plant "Nikola Tesla" is only 127 km^2, which corresponds to only 6% of the total areas of Gorski Kotar.

Lika is also a karst region, south of Gorski Kotar, situated between the mountain ranges Velebit, Pljesivica and Mala and Velika Kapela. The Lika region consists of several plateaus and karst polja of average altitude of 500 to 700 meters above sea level. The experimental region of the Senj Hydroelectric

Plant has a catchment area of 1100 km^2, of which three quarters lie between 550 and 800 meters. The peaks of Velebit reach an altitude of 1600m and protect the Lika region from maritime influences from the west.

3. THE MAIN CLIMATIC CHARACTERISTICS OF GORSKI KOTAR AND LIKA

3.1 Temperature

On the average the warmest parts of Lika and Gorski Kotar are the karst plains (so-called "polja") with temperatures somewhat less than 8°C. The peaks of surrounding mountains have an annual average of 3 - 4°C. The mountain peaks west of Licko polje have mean temperatures near -2°C in spring and in autumn near 5°C, which indicates a significant feature of this region, namely that spring is colder than autumn.

We should notice also that negative surface air temperatures at selected areas do not appear only in the summer season. The annual course of the -5°C isotherm had been ascertained by means of the nearby radiosounding stations at Zagreb and Split, located not more than 170 km from the experimental region. On the annual average the -5°C isotherm has a mean altitude between 2.2 and 4.5 km, and in winter there are days when it attains even 4 km. The surface temperatures in winter sometimes fall below -5°C, but on the average even then the height of this isotherm is 1.5 km. Analysis of the 0°C isotherm for Zagreb shows that in winter months its altitude lies between 2000 and 2600 m, and in July between 2200 and 4600 m.

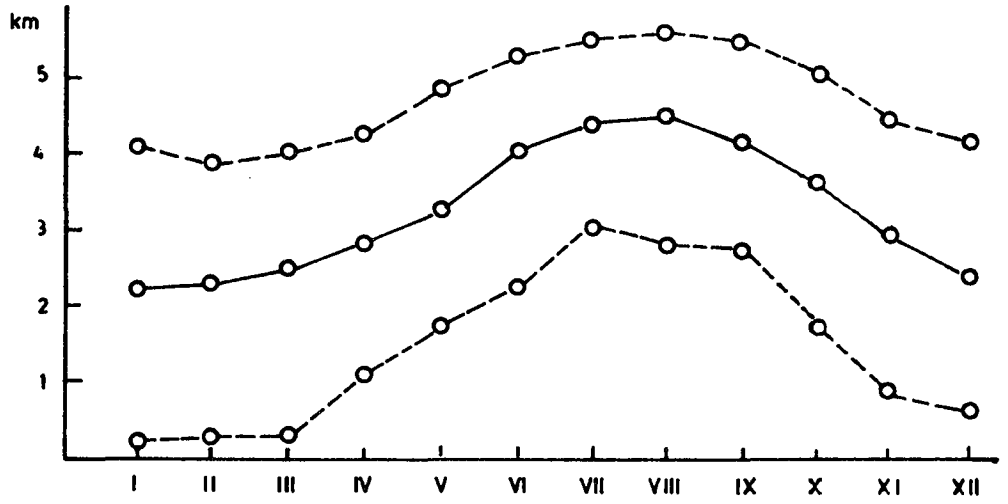


Figure 1.

Annual course of mean maximum, average and minimum heights of the -5°C isotherms above the region of Lika.

3.2 Predominant Synoptic Situations

The examination of the synoptic charts for the period 1956-1965 has shown that in the experimental regions on an annual average the synoptic situations appear with the following probability:

a)	anticyclones	20.4%
b)	ridges of high pressue	21.5%
c)	cyclones	22.1%
d)	low pressure troughs	6.4%
e)	weak pressure gradients	18.5%
f)	all others	11.1%

The seasonal frequencies of cyclones in Lika and Gorski Kotar are:

Spring	Summer	Autumn	Winter
26.5%	10.5%	19.3%	24.22%

In spring and autumn approximately one quarter of all days are influenced by cyclones, which explains the great variability of the weather patterns in these seasons. Although one may attribute moderate to high precipitation to cyclones, there are also situations with weak pressure gradients of a cyclonic type which bring large quantities of rain in more than 20% of all cases.

3.3 Cloudiness

The regions of Lika and Gorski Kotar may be regarded as the cloudiest areas of Croatia: in winter the average cloudiness is greater than 7/10. In general the region of Gorski Kotar has somewhat greater cloudiness than Lika. Of all seasons summer is characterized by the least cloudiness (4/10).

In order to assess the climatic potential for stimulation of rain, the data of three synoptic stations in these regions (Parg, Ogulin, and Gospic) were analyzed. The number of days in winter with mean cloudiness greater than 8/10 in these regions is 15-20 per month and in summer not less than 3-6 days. The most frequent cloud type is Sc, with the greatest probability of occurence in spring and autumn. Less frequently Cu clouds appear, and even less Ac clouds. The frequency of Ns clouds in winter is 10%.

Cu clouds occur most frequently in early afternoon hours of the summer season with a probability of 65%. The chances for more developed Cu clouds (Cu cong.) are 10%, and for Cb clouds only 5%. St clouds appear only in the colder part of the year with a probability greater than 10% regardless of the hour of the day.

The average height of stratiform clouds in the experimental regions in approximately 90% of all cases is 800 - 1000 m above the ground. All these clouds occurring with overcast skies bring no significant precipitation (in 50% of all cases less than 1 mm and never more than 10 mm in 24 hours). These periods of precipitation are mainly of quite short duration (less than 4 hours).

3.4 Precipitation

In the lower parts of Gorski Kotar the annual precipitation averages 2600 mm while at the plateau of Lika only about 1100 mm, which indicates the deficiency of precipitation in this area. November is the rainiest month of the year in Gorski Kotar with 300 mm, and in Lika with 150 mm. On the other hand, in the summer months of July and August one could expect 120-140 mm precipitation per month in Gorski Kotar and 50 mm in Lika. The analysis of the pentad sums of precipitation shows that a well pronounced drought period may be expected in both regions between the middle of July and the middle of August, from the last pentad in August till the middle of September, and in the fourth pentad of October. Well pronounced rainy periods fall between the end of April and the beginning of May and from the end of October till the middle of November. In summer cumuliform clouds could be seeded by airborne generators, but natural conditions seem to be not very favorable for it.

The analysis of days with less than 10 mm precipitation, that is, those situations when natural conditions for intensive precipitation processes are not favorable, shows that the augmented number of these days is bound for mountain areas of the experimental regions. In the most favorable cases in winter in Lika 14 days and in Gorski Kotar one day more when such limited precipitation could be expected.

In the Lika region, which has less precipitation than Gorski Kotar, there is not a single month during the year when there are not at least six days with weak precipitation; and in Gorski Kotar, 8 to 12 days.

Based on the assumption that future actions will occur mainly on days with stratiform clouds, one may assume that in the experimental areas of Lika and Gorski Kotar at least 70 to 100 days per annum will be favorable for rain stimulation.

In order to ensure a better evaluation of future rain stimulation action, the raingauge network was enlarged four years ago with 20 new raingauges and three recording raingauge stations, located mainly in the very sparsely populated areas. A large number of daily isohyet charts of the experimental regions was compiled by which the dependence of the daily precipitation upon the upper air flow at 850 mb was ascertained. Only those cases were considered which had the same direction for both as the wind at 850 mb and the gradient surface winds. Of all mean wind directions, only during northerly flow does the area of maximum precipitation not lie inside the experimental region. It was also found that the wind from the northeast quadrant brings much less precipitation than the winds from the southerly or westerly quadrants. With northeast winds in the experimental region of Gorski Kotar the daily quantities of rain do not exceed 5 mm/ 24 hour and in Lika, 3 mm/ 24 hour. On the other hand, southerly winds bring Gorski Kotar 25 mm and Lika 6 - 8 mm of daily precipitation on the average.

4. AN OUTLINE OF RECENT RESEARCH AND FUTURE ACTIONS

The completed investigations of climatic potential of the experimental regions in Lika and Gorski Kotar has confirmed our conviction that future rain

stimulation actions will bring positive results in the long run and that these actions should be made from the ground except in summer, then by airborne generators. Based upon the direction of predominant winds and orography in these regions, we have already located positions of more than 50 generators.

It is planned that during the next two years detailed research of natural conditions for stimulation of rain should be made. By means of new, specially erected radiosoundings station in Gospic and at nearby mountain peaks, the synoptical and physical conditions favorable for stimulation of rain will be examined. At Stipanov Gric (1200 m), which is situated in the middle of the experimental region of Lika, some measurements in microphysics of clouds will be performed. For this purpose an automatic SOULAGE type analyser for recording of ice nuclei will be installed; also, measurements of size spectrum of cloud drops and water content will be made. Routine observations and measurements of meteorological elements are also planned.

In this period all methods which may be used will be examined and evaluated. This also includes the methods of evaluating results of rain stimulation.

After the research period the actual operations are expected to start and last at least five years. Without doubt the results and experience of these activities will be of great value for future activities in rain stimulation in many regions of Yugoslavia.

- - - - -

ACKNOWLEDGEMENTS

The research on the climatic potential of the experimental regions was done by my colleagues Mmes. N. Sinik, E. Loncar and N. Plesko. This research is fully described in a large report (unpublished) for the Yugoslav community of power plants.

- - - - -

PHENOMENA OF PERSISTENCE OF ARTIFICIAL ICE-NUCLEI CONCENTRATION

Paolo Petti

SOREM - Societa Richerche Esperienze Meteorologiche
Roma

The Provincial Association of Defense Against Hail of Vicenza is organizing during the five-year period 1972-76, an anti-hail on the hillside and in the lowlands of the Province of Vicenza, covering an area of about 160 000 hectares (1600 km^2).

From a topographical point of view, this area is mainly flat, its Northern part, extending its foothills to the Pre-Alps, being an exception. The tableland of Asiago is bordered in the South by these Pre-Alps, whose Southern slopes are generally steep. The North-Western part of the region is characterized by a more modulating type of hill along the valleys of the Agno and Chiampo. South of Vicenza, there is another group of hills linking up with Berici mountains. Though from a planimetrical point of view, the area can thus be regarded as a plain, already this area and even more its Northern and the North-Western parts show a hillside character, which undoubtedly determinates the climate and the meteorological phenomena of the whole area, even in its lowest parts; in particular, the circulation of air at low and medium heights is definitely influenced by the orography.

The first operative period of the above-mentioned campaign started on the 15th of May and finished on the 31st of October 1972; the anti-hail operations were carried out by the S.O.R.E.M. by means of diffusion in the atmosphere of nucleant meterial (AgI) by using a combination of 34 ground-based generators, four mobile high powered generators and two aircraft.

Considering the fact that for these experiments a mixed technique is used (generators on the ground and aircraft), the measurement of the ice-nuclei concentration is of paramount importance, as it permits to establish with sufficient precision the way in which the nucleant material diffused by the generators, is spread through the atmosphere: since this determines the efficiency of the operation.

Therefore, during the first operative stage in the zone of Vicenza, systematic measurements of the ice-nuclei concentration of the atmosphere were carried out by means of the use of a fixed cold chamber.

The measurement station, installed in the Comune of Lusiana at about 700 meters above sealevel (figure 1), has a mixing cold chamber. Through the evaporation of water inside the cold chamber the necessary humidity reaches its point of saturation; in these conditions it is possible to maintain the temperature constant. In this type of cold chamber, type CFL/2, standardized with that used by the French scientists of the Observatory of Puy de Dôme, the ice-nuclei are counted by observing the crystals which develop in a sugary metastable solution.

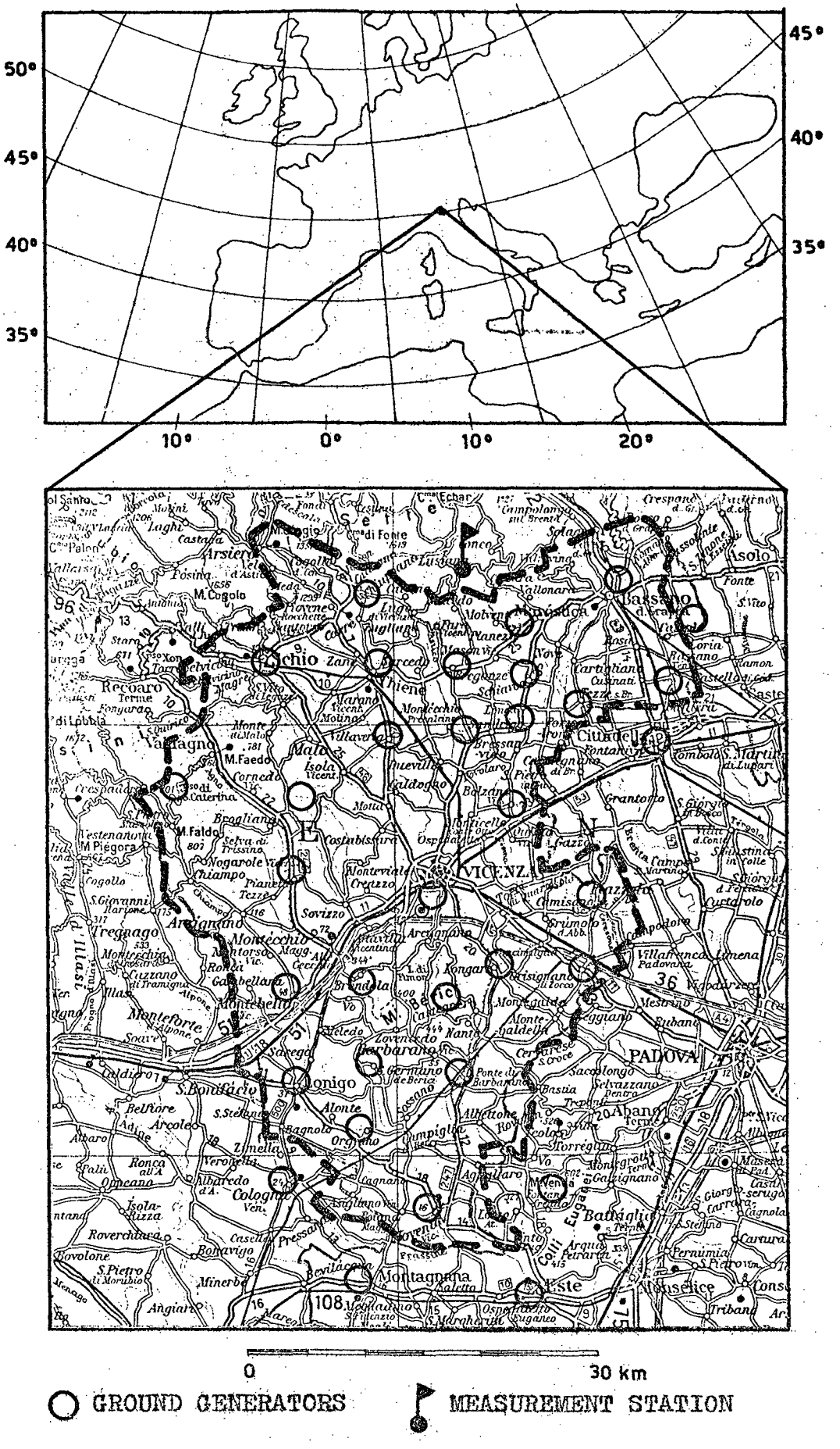


Figure 1. Experimental area of the campaign Vicenza

The temperature is controlled by means of 5 electrical thermometers linked to a source of electricity. It may vary from an ambient temperature to $-30^{o}C$. The equipment used in Lusiana is automatic and carries out a complete cycle of measurement every hour, the timing being regulated electronically. Moreover, this equipment has a camera which makes four photograms per hour to register the working temperature, the hour and the stage of the measurement and of course the crystals which have developed in the sump. The data obtained with this equipment may be said of high-level precision because any mannual intervention is completely excluded.

The cold chamber at Lusiana regulated at a standard temperature of $-21^{o}C$ was in function at that station from the 4th of August until the 30th of November 1972. During that period 1962 measurement tests were carried out.

When examining the results of the tests, one fact of great significance becomes evident, i.e. the different development of the ice-nuclei concentration during the days when the trials were carried out if compared to the days without.

During the days without trials, the values of the measurement tests are considerably inferior, at very low levels (approximately equal to the natural ice-nuclei concentration of the air). At various occasions, however, the material diffused by the generators is reactivated and circulates again even various days after the trials. One may deduct from this that the nucleant material remains active far beyond the period generally considered as a deadline for its breakdown and inactivation.

In fact, this happens frequently, especially when there is hardly any wind or completely calm weather, the reappearance of very high level concentration of ice-nuclei long after the trials, also repeatedly for a number of days.

This phenomenon (which we indicate as "persistence"), probably linked with the arising of instabilities or with a change in the anemological conditions, in general does not coincide with constant high levels of the ice-nuclei concentration usually, once the generators stop working, especially during the night, a fall to levels equal to natural values takes place.

The next day and often during the following days, with the progressive heating up, strong increases in the value of the ice-nuclei concentration occur, sometimes reaching peaks alternated with lower values.

Figure 2, which shows the development of the ice-nuclei concentration of the air from 22 to 27 August 1972, shows what has been said before, in particular the phenomenon of the persistence. The meteorological situation during the afternoon and the evening of 22 August was characterized at height by a moderate flow of rather cold, northerly air currents over the Northern regions of Italy, accompanied by thunderstorms of high intensity in certain areas. During the following days, high atmospheric pressure gradually developed over the whole of Italy, with good weather conditions, on

the ground and at the lower strata the wind was calm, at greater heights the winds were weak. The graph shows that during the 22nd of August (up to the measurement taken at about 19.00 hours) the values remain relatively low. During the course of the evening, from 20.00 hours onwards, immediately following trials in that region, the diffusion of nucleant material, favoured by anemological conditions and by strong instability, shows very high values of ice-nuclei concentration which persist for various hours. During the night this is followed by a fall to levels similar to natural values; a similar situation was shown by the measurement taken up to 18.00 hours of the 23rd of August. During the evening of the 23rd of August, following localized trials carried out by aircraft only, the value of the ice-nuclei concentration increases considerably. During the following days (24,25 and 26 August 1972) the phenomenon of persistence is clearly discernible; during the night and the first hours of these days, in fact, the values of the measurements are low in general; during the middle part of the day, however, the gradual warming up favours the reactivation of the artificial ice-nuclei even a few days after the last trial, showing strong increases of the ice-nuclei concentration with very high peaks. From all this it becomes evident that the AgI does not lose its nucleant capacity, as a result of fotolitic breakdown, except to a very small degree. Another strong increase of ice-nuclei concentration around midnight of the 26th of August; in this case, however, the effect of the trial of the ground based generators, carried out a few hours before, is evident.

Figure 3 shows the measurements of the ice-nuclei concentration carried out at the station of Lusiana during a period when the anti-hail trials were stopped (the last took place towards the end of September 1972).

The measurement tests carried out from 5 to 9 November 1972 were rather regular, with values maintained in general at very low levels and which at any rate did not go beyond the limits of possible natural variability.

During the period under review a vast anticyclonic area at all heights covered the Mediterranean zone and Central Europe, showing subsidence phenomena. Over the zone of Vicenza foogy weather prevailed, favoured by the persistence of inversions in the low strata with no wind.

The phenomenon of persistence, brought to light by the measurements of Lusiana, has a considerable scientific interest, as it leads to the supposition that the real disactivation of the nuclei AgI in a natural environment is considerably less (perhaps by various degrees) than that shown by the laboratory tests. With regard to the techniques of the trials, it moreover has an important practical significance because it shows that the possible effects of the insemination trials, for a certain region, are far longer lasting than had been thought possible so far.

During the first operative stage of the Vicenza campaign also 6 cycles of measurements of the ice-nuclei concentration were carried out at medium heights by means of the cold chamber AVIO installed in aircraft. The purpose of these tests was to ascertain the way of diffusion of the nucleant material produced by the generators and other means and to check on the quality

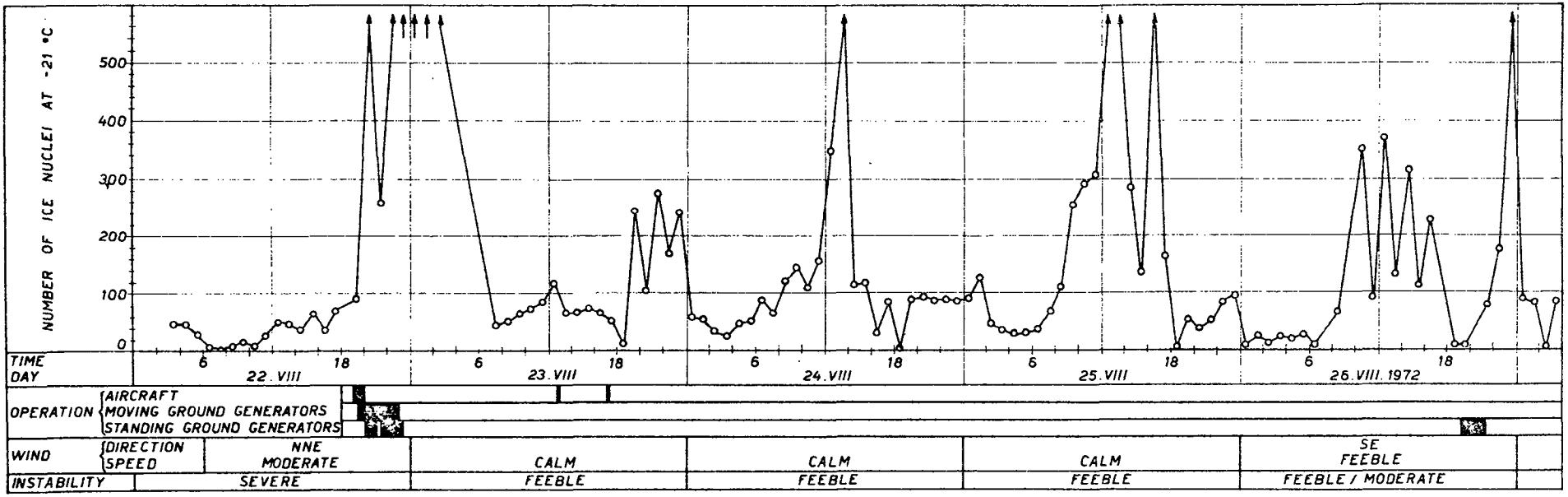

NUMBER OF ICE NUCLEI AT -21 °C
500
400
300
200
100
0
TIME
DAY
6
18
22. VIII
23. VIII
24. VIII
25. VIII
26. VIII. 1972
OPERATION
AIRCRAFT
MOVING GROUND GENERATORS
STANDING GROUND GENERATORS
WIND
DIRECTION
SPEED
NNE
MODERATE
CALM
SE
FEEBLE
INSTABILITY
SEVERE
FEEBLE
FEEBLE / MODERATE

FIG. 2

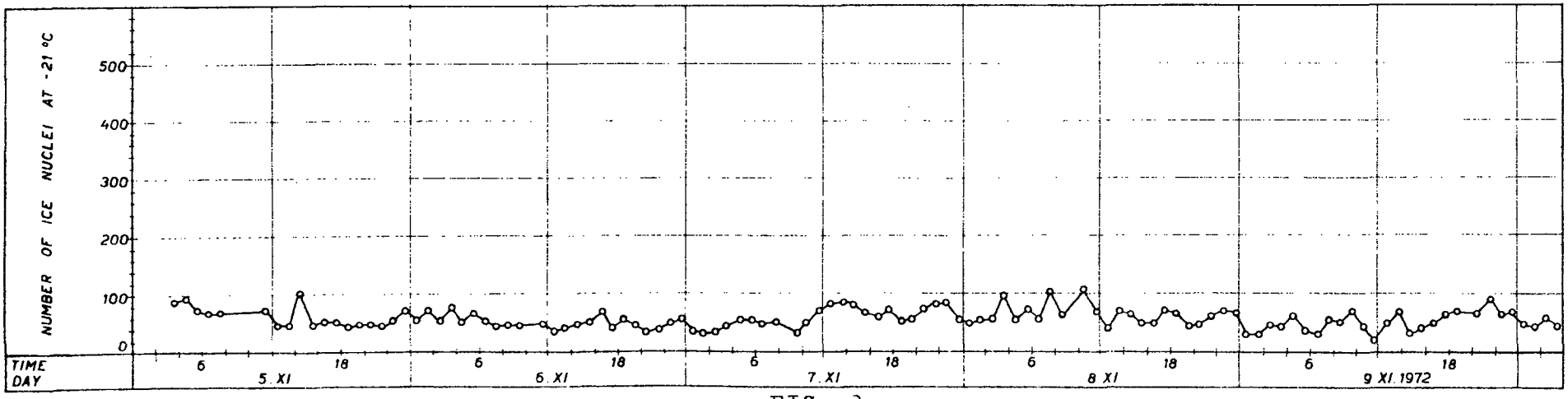

NUMBER OF ICE NUCLEI AT -21 °C
500
400
300
200
100
0
TIME
DAY
6
18
5. XI
6. XI
7. XI
8 XI
9 XI. 1972

FIG. 3

of the equipment and the materials used.

Figure 4 shows the statistical distribution of the results of the 31 measurements of the ice-nuclei concentration at height, carried out in the course of the six cycles mentioned above; the distribution is divided in groups of multiples of the natural mean concentration present in the zone. It should be kept in mind that the lower groups contain various measurements (almost all those at the beginning and some at the end of each cycle) carried out in zones definitely not reached by artificial nuclei of AgI. As the distribution is clearly bimodal, it may be supposed that there are two different ways of upward diffusion of the nucleant materials: one is due to the small-scale turbulence which dilutes the particles progressively in a rather uniform way; the other characterized by the nucleant materials forming groups which rise up and preserve also at greater heights a strong concentration.

Considering that the greater part of the measurements in question took place with stable weather, with almost no turbulences and upward currents, the very significant results obtained lead to the conclusion that the anti-hail trials permit to increase the ice-nuclei concentration of the air up to a considerable height, even in the most unfavorable conditions of apparent absence of vertical movements in the zones above the ground-based and mobile generators of nuclei AgI.

- - - - - -

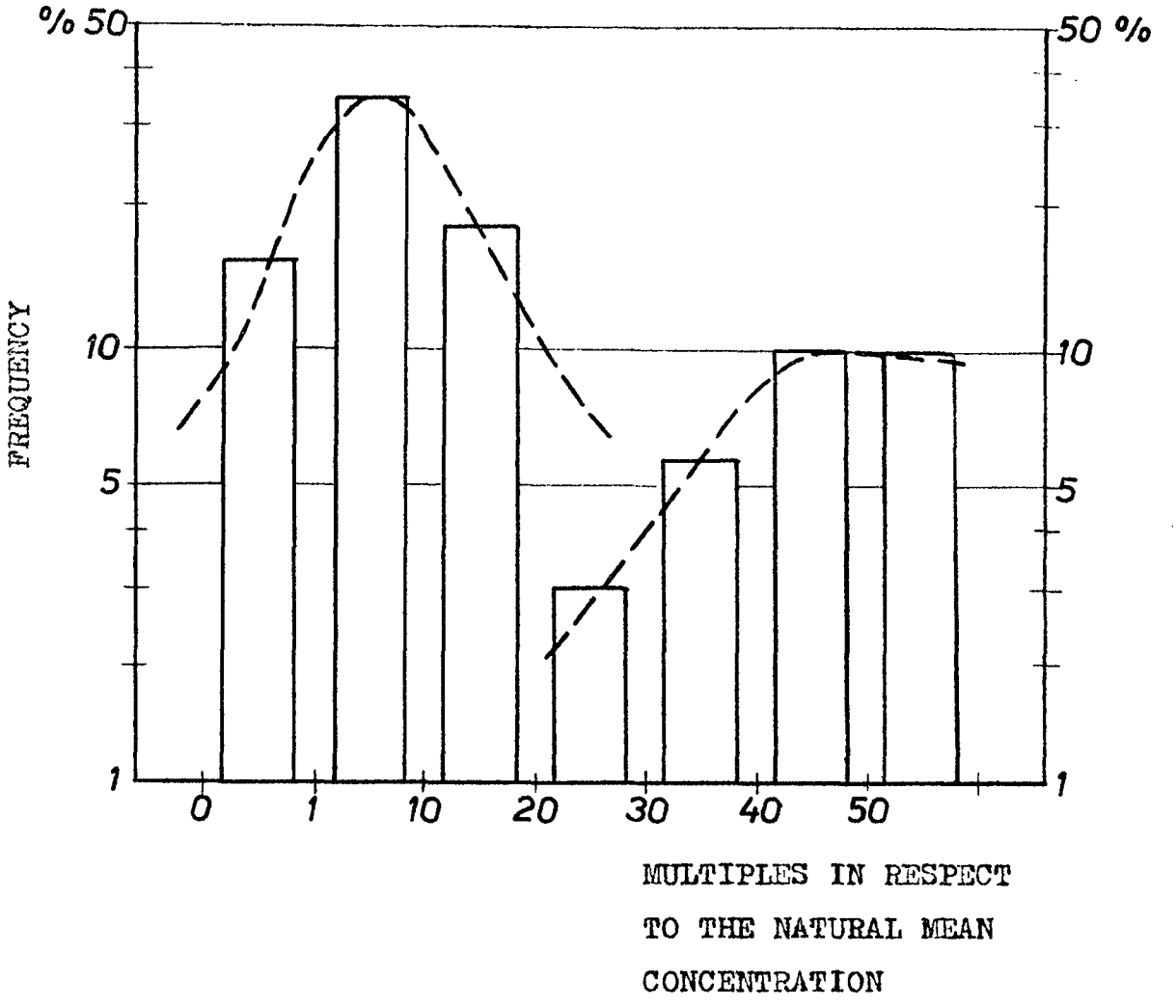

% 50
50 %
FREQUENCY
10
5
1
10
5
1
0
1
10
20
30
40
50
MULTIPLES IN RESPECT
TO THE NATURAL MEAN
CONCENTRATION

FIG. 4

THE RELATIONSHIP OF SOCIO-DEMOGRAPHIC CHARACTERISTICS AND ATTITUDES TOWARD WEATHER MODIFICATION: THE SOUTH DAKOTA STUDY, 1972

Barbara C. Farhar

Institute of Behavioral Science
University of Colorado
Boulder, Colorado 80302

INTRODUCTION

South Dakota had an operational state weather modification program during the summer of 1972. About a third of the State's counties chose to be included in the program. Its dual aims were hail suppression and rain augmentation. Research on the social implications of the weather modification program is being carried out by the Institute of Behavioral Science, University of Colorado.

The interview schedule used in this study was designed to collect data on attitudes toward weather modification in general, belief in the efficacy of weather modification, knowledgeability about programs, and respondents' evaluation of those programs.

In order to determine whether there were any significant differences among various groups in the populationof South Dakota with regard to the key variables in the study, the relationships between selected demographic characteristics and these variables were examined.

The demographic characteristics used in this analysis were as follows: sex, age, education, occupation, family income, religious preference, and area (the area of the state in which the respondent resided). These characteristics were compared to twenty-two selected items from the interview schedule.*

The key variables were intended to tap the following dimensions:

(1) Attitudes toward weather modification in general.

(2) Belief in the efficacy of cloud seeding for rain augmentation and hail suppression.

(3) Knowledgeability about the local, non-local (the rest of the state) and the State Weather Modification Program.

(4) Evaluation of the local, non-local and State Programs. (The local and non-local programs were actually conducted under the auspices of the State Program; that is, the State and local programs organizationally comprise the same entity.

---

*For a list of the items, see Appendix A.

The research on which this article was based was conducted under research grant #GA-28364 from the National Science Foundation, J. Eugene Haas, Princ. Invest.

(5) Whether or not respondents knew there was cloud seeding prior to the Rapid City flood of June 9, 1972, and to what degree they attributed the flood to the cloud seeding.

The chi square test for nominal data was used to determine whether there were any significant relationships between these variables in our sample. Of the 154 relationships examined, 71 or 46% were significant with alpha $\leq .10$. Fifty-four or 35% were significant with alpha $\leq .05$. Sex, age, education, and occupation appeared to be the most powerful demographic variables in this group.*

THE SAMPLE

The 1970 census shows the population of the State of South Dakota at 666,000. There are 330,000 males and 335,000 females.** The sex ratio is 98.4 males per 100 females in the total population.

The sample used in this study is an area probability sample (random sample) selected from lists of households in the counties participating in the South Dakota State Weather Modification Program, 1972 season. Within the limits of standard statistical error, it is possible to generalize from this sample to the population of the counties involved.

The data used in this analysis were collected in three rounds of interviewing. Demographic information was collected in January and April, 1972, prior to the weather modification season. The attitude and knowledge items analyzed here were administered in September, 1972, following the weather modification season. All 368 respondents comprising the September sample had been interviewed at least once before.

Analysis of the demographic characteristics of the January - April samples and the September sample shows that the latter had not changed to any significant degree because of sample losses. The population represented by this sample appears to be predominantly middle-aged, middle class, Protestant and extremely stable, with strong community ties.

The demographic variables will be presented one at a time, with a summary of the significant relationships found for each one.

Sex

Differentiating responses to key items on the basis of sex gives rise to some interesting results. Several significant differences were found.

Both males and females tended to agree with statements in favor of weather modification and scientific experimentation. In all cases, however, males agreed more strongly. (See Tables 1 and 2, for example.)

---

* Appendix B contains a detailed breakdown of the number of significant relationships found by demographic variables.

** Figures are rounded. Source: Statistical Abstracts of the U.S., 1972.

Statements opposed to weather modification elicited a different pattern of response by sex. The following items were, in general, viewed more favorably by females and more negatively by males. (See Tables 3, 4 and 5.)

(1) Even when carefully controlled, cloud seeding programs are very likely to upset the balance of nature.

(2) Cloud seeding probably violates God's plans for man and the weather.

(3) Man should take the weather as it comes and not try to alter it to suit his needs or wishes.

Table 1.

South Dakota State and county officials should feel free to use such things as cloud seeding if it might help farmers avoid crop losses.

	% Males	% Females	% Totals
Strongly Agree	20	9	14
Agree	54	51	52
Unsure	4	14	9
Disagree	15	18	17
Strongly Disagree	7	8	8
	100	100	100
N =	183	185	368

$\chi^2 = 17.7211$ d.f. = 4 $p < .005$

Table 2.

If weather is a problem to farmers, it is appropriate to try to directly control extreme weather conditions by using the most effective techniques known -- e.g., cloud seeding to increase rain if moisture is needed, etc.

	% Males	% Females	% Totals
Strongly Agree	24	10	17
Agree	49	49	49
Unsure	5	11	8
Disagree	15	20	18
Strongly Disagree	7	10	8
	100	100	100
N =	183	185	368

$\chi^2 = 17.7388$ d.f. = 4 $p < .005$

Table 3.

Even when carefully controlled, cloud seeding programs are very likely to upset the balance of nature.

	% Males	% Females	% Totals
Strongly Agree	9	15	12
Agree	31	41	36
Unsure	18	21	20
Disagree	31	21	27
Strongly Disagree	9	2	5
	100	100	100
N =	183	185	368

$\chi^2 = 16.6765$ d.f. = 4 $p < .005$

Table 4.

Cloud seeding probably violates God's plans for man and the weather.

	% Males	% Females	% Totals
Strongly Agree	12	17	15
Agree	20	37	28
Unsure	12	12	12
Disagree	43	31	37
Strongly Disagree	13	3	8
	100	100	100
N =	182	185	367

(Missing data = 1)

χ^2 = 24.2135 d.f. = 4 p < .001

Table 5.

Man should take the weather as it comes and not try to alter it to suit his needs or wishes.

	% Males	% Females	% Totals
STRONGLY AGREE	8	13	10
AGREE	23	34	28
UNSURE	5	9	7
DISAGREE	53	41	48
STRONGLY DISAGREE	11	3	7
	100	100	100
N =	183	185	368

χ^2 = 19.0805 d.f. = 4 p < .001

Both sexes agreed that "man will probably never succeed in changing the weather to suit his needs or wishes." But, both sexes also disagreed with, "We shouldn't use such things as cloud seeding even if it does work."

The results appear to indicate, overall, that women are more conservative than men in their attitudes toward weather modification. The nature of this conservatism appears to be a concern about potential natural imbalance resulting from cloud seeding efforts. This conservatism parallels the "religio-natural orientation" described earlier by Pfost (1972).[1]

Both men and women expressed a belief in the efficacy of cloud seeding with regard to rain augmentation; indeed, the vast majority of men believed that cloud seeding works to increase moisture while the women were somewhat more skeptical. (See Table 6.) Both sexes were less sure about the efficacy of seeding for hail suppression.

Table 6.

Do you think cloud seeding works -- that is, do you think it can actually increase moisture?

	% Males	% Females	% Totals
No	4	8	7
Perhaps, but I doubt it	4	4	4
I think so, but I'm not sure	17	20	18
Yes	66	46	56
Don't know	9	22	15
	100	100	100
N =	183	185	368

$\chi^2 = 18.7106$ d.f. = 4 $p < .001$

With regard to the local program, there was no significant difference by sex on assessment of success. Sixty percent of the males and 49% of the females thought their local program was successful. However, assessment of non-local programs showed a significant difference ($p < .05$) by sex. Among males, 41% thought they were successful and 23% of females agreed. Females were more than twice as likely as males to see the non-local programs as failures.

[1] "Social Implications of the National Hail Research Experiment," 1971 Final Report, February 8, 1972, National Center for Atmospheric Research, Donald Pfost, Project Director and J. Eugene Haas, Principal Investigator.

Males were more likely to have heard about the South Dakota State Weather Modification Program than females ($p < .05$). Of those who felt they were most informed about the Program, over three-quarters were males ($p < .10$). Evaluation of the South Dakota State Weather Modification Program differed significantly by sex ($p < .005$). Males were more favorable to the Program (66% compared to 47% for females). Males said they were likely to do something to actively support the Program more than did females ($p < .01$).

With regard to the Rapid City flood, there was no significant difference between the sexes in knowledge of the cloud seeding event. There was, however, a significant difference ($p < .001$) in the way men and women viewed the relationship between cloud seeding and the flood. Men were more likely to indicate that there was "probably not" or "definitely not" a relationship between cloud seeding and the flood (69%), while 18% thought there was some relationship. Over a third of the women, on the other hand, felt there was a causal link involved; 25% of them felt the seeding was a "contributing cause."

In general, the picture that emerges, when key results are differentiated by sex, is that males show more favorable attitudes toward weather modification in general; they are more knowledgeable about programs in locales other than their own and about the State Program; and their judgement about the State Program is more favorable. In addition, they are significantly more likely to exonerate cloud seeding as a cause of the Rapid City Flood.

These findings suggest certain ways in which a public education campaign on weather modification might be conducted to reach a group potentially less favorable to it: women. Newspaper articles on the work of women meteorologists (such as the one which appeared in the March 19, 1973 issue of the Boulder Daily Camera on women doing meteorological work for the National Oceanic and Atmospheric Administration), how the weather affects food prices and thus what impact weather modification might have on food prices, current legislation on weather modification, weather modification and the environment, and so on, would be of particular interest to this group. Daytime radio interviews and news items would be more likely to reach the audience of women.

Age

The under-25 age group differed significantly from the rest of the population in attitudes toward weather modification in general. On three items, this age group disagreed significantly more than the other groups.

(1) Even when carefully controlled, cloud seeding programs are very likely to upset the balance of nature. ($p < .01$)

(2) Cloud seeding probably violates God's plans for man and the weather. ($p < .10$)

(3) Man should take the weather as it comes and not try to alter it to suit his needs or wishes. ($p < .10$)

The two age groups from 56 to 75 agreed significantly more with the item: "Man will probably never succeed in changing the weather to suit his needs or wishes." ($p < .10$)

However, age groups from 46 to 55 and 66 to 75 were somewhat more skeptical than any of the other age groups about the efficacy of cloud seeding. ($p < .05$).

The under-25 and over-75 age groups were least likely to have heard of the South Dakota State Weather Modification Program, ($p < .005$). Of those who had heard of the program, there was no significant difference by age in their degree of knowledgeability. There was also no difference by age with regard to judgement on programs or the Rapid City flood items.

In general, the under-25 group appeared to be slightly more favorable toward weather modification than their elders. These youth in their responses to our questions, did not exhibit the anti-scientific bias thought to be prevalent in their age group elsewhere in the country. The difference between age groups appear to be relatively few in general. Age does not appear to account for as much variation in response as sex.

Educational Level

Information was obtained from respondents as to the highest level of education they had completed: first through sixth grade, junior high school, some high school, high school graduate, some college, or college graduate and higher.

When educational level is used to differentiate the sample, definite patterns of response emerge. In general, the higher the educational level, the more favorable is the response to weather modification and to scientific experimentation. For example, college graduates are most likely to agree with, "Man should use scientific knowledge to deal with problems whenever and wherever possible." ($p < .025$)

College-educated respondents are most likely to disagree with statements such as, "Man should take the weather as it comes and not try to alter it to suit his needs or wishes." College graduates showed 85% disagreement, compared to 54% for the sample as a whole. ($p < .005$)

In addition, college graduates are significantly more likely to believe in the efficacy of cloud seeding. Ninety percent of the college graduates in the sample believed cloud seeding can actually increase moisture ($p < .005$). College graduates are also somewhat more likely to think hail suppression works (50% compared to 27% for the rest of the educational levels, $p < .10$).

Knowledgeability about local programs was slightly higher as education increased ($p < .10$). Knowledgeability of non-local programs also increased by educational level. (See Table 7.) The same finding occurred for the State Program: the higher the educational level, the more likely the respondent had heard of the weather modification program ($p < .005$).

However, there was no significant difference in evaluation of programs by educational level. Judgement of the local program showed college graduates least likely to term the program a failure (5% compared to 12% for the sample as a whole). For the non-local and State programs there was no indication that educational level affected favorability toward them.

Table 7.

Since we've last talked to you, have you heard of any cloud seeding programs in any community in South Dakota besides your own community and nearby?

	1-6	7-9	10-11	HS grad.	Some coll.	Coll. grad.	Total
Yes	43	50	50	64	66	79	63
Don't know	0	6	12	7	1	2	5
No	57	44	38	29	33	19	32
	100	100	100	100	100	100	100
N =	7	66	24	140	79	48	364

(missing data = 4)

χ^2 = 20.2487 d.f. = 10 $p < .05$

The higher the education level of the respondent, the more likely he was to know that there was cloud seeding prior to the Rapid City flood. (See Table 8.) However, there was no significant difference by educational level in whether the respondents saw a causal link between the cloud seeding and the flood.

Table 8.

As far as you know, was there cloud seeding in the Rapid City area immediately prior to the flood?

	1-6	7-9	10-11	HS grad.	Some Coll.	Coll grad.	Total
Yes	43	62	66	66	78	94	71
No	57	26	17	25	17	4	21
Don't know	0	12	17	9	5	2	8
	100	100	100	100	100	100	100
N =	7	68	23	140	78	48	364

(missing data = 4)

χ^2 = 27.3686 d.f. = 10 $p < .005$

In general, then, educational level appears to be significantly related to general favorability toward weather modification, to knowledgeability about programs, and to belief in efficacy. It does not appear to be related to judgements about programs, however.

Occupation

Information on occupations was obtained that enabled us to divide the sample into nine groups: (1) unemployed, (2) operatives and kindred, (3) craftsmen, foremen and kindred, (4) clerical and kindred, (5) owner, managerial and kindred, (6) farmer, (7) rancher, (8) professional, technical and kindred, and (9) housewife.

Owners/managers and professional technical workers were slightly more likely than other occupational groups to agree that it is appropriate to try to directly control weather conditions through cloud seeding. Ranchers, although not disagreeing with the item, were more likely to be uncertain about it ($p < .05$).

For "Even when carefully controlled, cloud seeding programs are very likely to upset the balance of nature," craftsmen/foremen and ranchers were the most likely of the occupational groups to disagree ($p < .025$).

Craftsmen/foremen and housewives were the two groups most likely to agree that "Cloud seeding probably violates God's plans for man and the weather." Professionals, ranchers, and clerical workers were the three groups most likely to disagree ($p < .005$).

Ranchers (100%) and owners/managers (86%) were more likely than other groups to be favorable to scientific experimentation with cloud seeding ($p< .025$). Housewives and craftsmen/foremen tended to be less favorable to experimentation with cloud seeding.

The sample as a whole tended to agree with the item: "Man will probably never succeed in changing the weather to suit his needs or wishes." Craftsmen/foremen were slightly more likely to disagree with this item (31%) as were professional/technical workers (29%). Housewives agreed with it more than the other groups (72%). Other groups agreeing with the statement were farmers and operatives ($p <.001$).

Professional/technical personnel disagreed more strongly than other groups that "We shouldn't use such things as cloud seeding even if it does work." ($p < .05$)

There appeared to be no significant differences among occupational groups on belief in the efficacy of cloud seeding.

There was no apparent difference among the groups with regard to knowledgeability about the local and non-local programs. Of those who said they had heard of the South Dakota State Weather Modification Program (N=270), significantly more ranchers claimed to be "fairly well informed," (50% compared to 8% for the sample as a whole). The occupational group least informed was the operatives ($p< .05$). Greatest favorability to the South Dakota State

Weather Modification Program was shown by ranchers (77% compared to 57% for the sample as a whole). The least favorable group was housewives (40% in favor, $p < .01$).

Of all the occupational groups, ranchers were most likely to say they didn't know whether there was cloud seeding prior to the flood. (44% compared to 8% for the entire sample, $p < .01$). There was no difference by occupation in attributing the Rapid City flood to cloud seeding.

When we compare responses of farmers and ranchers, it is interesting to note their differences. In general, ranchers appear to have been somewhat more favorable to weather modification and scientific experimentation than farmers.*

No one occupational group stands out as being significantly different from the others in terms of the key variables examined here. While professionals and ranchers show a slight inclination to be more favorable toward weather modification and housewives to be less favorable, no overall pattern of differences emerges from the data on occupational groups.

Family Income

Information was obtained from 325 respondents as to their average annual family income after taxes. The following nine categories were used: (1) under $3,000 (2)$3,000-$4,999 (3) $5,000-$6,999 (4) $7,000-$8,999 (5) $9,000-$10,999 (6) $11,000-$12,999 (7) $13,000-$14,999, (8) $15,000-$20,000 and (9) over $20,000.

Respondents with incomes under $5,000 were more likely to agree with the item: "Man should take the weather as it comes and not try to alter it to suit his needs and wishes," (59% compared to 37% for the sample as a whole). The group having an income between $13,000 and $15,000 disagreed most with the item ($p < .01$).

The two groups whose income fell between $3,000 and $5,000 tended to disagree that scientific experiments usually produce results useful to man. The four upper income groups were virtually unanimous in their agreement with this item. The data show a tendency for the lower income groups to exhibit skepticism about the efficacy of science ($p < .05$).

This tendency is repeated for the item "Man will probably never succeed in changing the weather to suit his needs or wishes." The lower income groups are in more agreement than the upper income groups. The highest income group (over $20,000) was more inclined to be unsure (40% compared to 14% for the sample as a whole, $p < .01$).

Table 9 exhibits the slight anti-weather modification tendency of the lower income groups and the relative favorability of the upper income groups. (See Table 9.)

---

*It is possible that ranchers who are dependent on natural precipitation for pasture and hay are more favorable because of possible rain increases. Farmers may be less dependent on natural precipitation because of their ability to control moisture through irrigation. However, this must remain a conjecture at this time.

Table 9.

We shouldn't use such things as cloud seeding even if it does work.

	Increasing income ⟶									
	1	2	3	4	5	6	7	8	9	Total
Strongly Agree	2	18	2	3	2	0	0	0	0	4
Agree	17	18	13	7	12	8	0	22	20	13
Undecided	9	9	9	9	6	0	16	0	10	7
Disagree	63	50	65	61	68	76	42	61	60	62
Strongly Disagree	9	5	11	20	12	16	42	17	10	14
	100	100	100	100	100	100	100	100	100	100
N =	46	44	54	67	49	25	12	18	10	325

$\chi^2 = 54.1811$ d.f. = 32 $p < .005$

Belief in efficacy for rain augmentation and hail suppression is slightly greater among the higher income groups ($p < .10$ and .05, respectively).

There were no significant differences among the income groups with regard to knowledgeability and evaluation of the local and state programs. There is a slight suggestion that upper income respondents were more aware that cloud seeding took place prior to the Rapid City flood ($p < .10$). However, they were just as likely as the lower income groups not to assign blame for the flood on cloud seeding.

In general, the data on income groups suggests a slight tendency for upper income groups to view weather modification more favorably than lower income groups. This pattern does not find compelling support in the data, however.

Religious Preference

Our respondents were asked to indicate their religious affiliation according to the following categories: (1) Catholic, (2) Methodist, (3) Baptist, (4) Presbyterian, (5) United Church of Christ, (6) Lutheran, (7) Other and (8) No religious affiliation.

We were particularly interested to see if religious preference would make a difference on items such as "Cloud seeding probably violates God's plans for man and the weather." No significant pattern of differences by religious preference were found, either in the attitude items, or among any of the other key variables.

It is apparent that religious preference is not a good predictor of attitudes, knowledgeability, or judgement with regard to weather modification.

Area

The sample was drawn from three areas of the State. Area 1 included Pennington and Custer Counties (the Rapid City area) in the western part of the State. Area 2 included seven counties in the central region near Pierre, the State Capital. Area 3 was comprised of eleven eastern counties, including the Sioux Falls urban area.

Area 1 (Rapid City area) residents were far more likely to be aware of a local cloud seeding effort (see Table 10). Similarly, Area 3 residents were far more likely to be aware of cloud seeding elsewhere in the state ($p < .001$), (see Table 11).

Table 10.

Since we last talked to you, has there been any cloud seeding in your community or nearby?

	Area			
	1	2	3	Total
Yes	81	47	23	36
Don't know	13	11	19	16
No	6	42	58	48
	100	100	100	100
N =	52	72	244	368

$\chi^2 = 70.9582$ d.f. = 4 $p < .001$

Table 11.

Since we've last talked to you, have you heard of any cloud seeding programs in any community in South Dakota besides your own community and nearby?

	Area			
	1	2	3	Total
Yes	14	61	74	63
Don't know	2	8	5	5
No	84	31	21	32
	100	100	100	100
N =	51	71	243	365

(missing data = 3)

χ^2 = 78.3491 d.f. = 4 p < .001

Area 3 (eastern) residents were more likely to judge the non-local program a failure than the other groups ($p < .10$). They might well have been thinking of the flood; however, the tendency is not strong.

Rapid City area residents (Area 1) were significantly more aware that cloud seeding took place before the flood ($p < .025$). However, there was no difference by area in attributing the flood to cloud seeding.

Other than the knowledgeability items which can easily be connected to events in Rapid City in June, 1972, there were no significant differences by area in attitudes toward, belief in efficacy, or in evaluation of weather modification and the State Program.

SUMMARY

The findings of the South Dakota study vis-a-vis socio-demographic variables suggest that the single most favorable individual would be a relatively young, upper-middle class, well-educated male rancher or professional earning $20,000 a year. Obviously, no single individual fits the composite picture. But the findings are suggestive of certain elements of the population who might conceivably be more favorable or more opposed by virtue of their position in the social structure. They indicate clearly that certain socio-demographic variables should not be ignored when public opinion is to be considered.

Another important variable not considered in our study is ethnicity. We did not collect data on this potentially important structural component. It is impossible to say whether ethnicity would be as important as sex, age, or educational level in accounting for attitudes, knowledgeability, and favorability.

- - - - -

APPENDIX A

Selected Variables: Items From the Interview Schedule

1. If weather is a problem to farmers, it is appropriate to try to directly control extreme weather conditions by using the most effective techniques known, e.g., cloud seeding to increase rain if moisture is needed, etc.

2. Even when carefully controlled, cloud seeding programs are very likely to upset the balance of nature.

3. South Dakota State and county officials should feel free to use such things as cloud seeding if it might help farmers avoid crop losses.

4. Cloud seeding probably violates God's plans for man and the weather.

5. Man should use scientific knowledge to deal with problems whenever and wherever possible.

6. It is a good idea for scientists to experiment with cloud seeding so we can find out if it really does work -- to see if it does increase moisture, etc.

7. Man should take the weather as it comes and not try to alter it to suit his needs or wishes.

8. Scientific experiments in general usually produce useful results -- produce things that are helpful to man.

9. Man will probably never succeed in changing the weather to suit his needs or wishes.

10. We shouldn't use such things as cloud seeding even if it does work.

11. Do you think cloud seeding works -- that is, do you think it can actually increase moisture?

12. Do you think cloud seeding can actually suppress hail?

13. Since we last talked to you, has there been any cloud seeding program in your community or nearby?

14. In your opinion, was the cloud seeding effort a success or a failure?

15. Since we've last talked to you, have you heard of any cloud seeding programs in any community in South Dakota besides your own community and nearby?

16. In your opinion, was the cloud seeding effort a success or a failure?

17. Have you ever heard of the Weather Modification Program of the State of South Dakota?

18. (If yes), how well informed do you feel you are about the program?

19. Based on your understanding of the South Dakota State Weather Modification Program, how do you feel about the Program?

20. If there is a State cloud seeding program proposed for your area next summer, do you think you will do anything to support or oppose it?

21. As far as you know was there cloud seeding in the Rapid City area immediately prior to the flood?

22. Do you think there was a relationship between the cloud seeding and the flood?

APPENDIX B

Number of Significant Relationships
in a Comparison of 7 Demographic
and 22 Selected Variables

Demographic Variable	Selected Variables Number Significant at $\alpha \leq .05$	$\alpha \leq .10$	Total
Sex	15	3	18
Age	5	4	9
Education	11	2	13
Occupation	10	2	12
Family Income	5	2	7
Religious Preference	2	1	3
Area	6	3	9
Totals	54	17	71

- - - -

FACTORS RELATED TO ATTITUDES TOWARD WEATHER MODIFICATION PROGRAMS

Dr. Orville Lanham
Jerome Rosonka

Prepared for
The South Dakota Weather Control Commission*

Factors Related to Attitudes Toward Weather Modification Programs

"Have you ever visited the storeroom where I kept the snow and hail?... Who dug a channel for the pouring rain and cleared the way for the thunderstorm? Who makes rain fall where no one lives? Who waters the dry and thirsty land so that grass springs up? Can you shout orders to the clouds and make them drench you with rain? And if you command lightning to flash, will it come to you and say, 'At your service"? Who is wise enough to count the clouds, and tilt them over to send the rain, rain that hardens the dust into lumps?"

Job for Modern Man, 1971

If these questions were asked of a 20th century Job, who just happened to be a pure or applied scientist working with weather modification programs, the probability of a favorable answer would be very high. Building upon the post World War II research of Schaefer that discovered supercooled clouds could be seeded with dry ice to produce rain and snow, the present state of the art involves activities on many different fronts. National Science Foundation report of 1968 reported an expenditure of 11 million dollars for 65 weather modification projects. Projects funded included seeding for increased rainfall, for decreased hail, orographic seeding of winter storms over mountain ranges for increased snowpack, seeding for the suppression of lightning storms, seeding of hurricanes to decrease their intensity, and seeding of cold fog over airports to permit scheduled arrival and departure of commercial air traffic. Many of the programs are experimental in nature, and designed to provide scientists with knowledge of atmospheric physics and dynamics of clouds models. Along with the scientific investigation, operational weather modification programs have been conducted with voluntary associations of farmers supporting a cloud seeder during times of drought, and in South Dakota a statewide program has been designed to seed the entire state.

Because precipitation is highly variable in the Northern Great Plains -- Wyoming, Montana, North Dakota, South Dakota, and Nebraska, these states have been among the first to support operational weather modification programs. In the early 1950's, the support for such programs came from voluntary associations of farmers who supported local cloud seeding companies.

---

*Based on research conducted under Division of Atmospheric Water Resources Management, Bureau of Reclamation, Contract No. 14-06-D-7240

At one time over 60 percent of the state of South Dakota was seeded under such projects, and the operator used ground based generators (Williams, 1973). Agriculture in these states is the major industry, and drought and hail damage to crops affect the economy of the entire state. Rainfall variation in South Dakota is from a low of 14 inches average per year in the Northwest to 24 inches in the Southeast. Drought is a major concern because precipitation is marginal for most crops. In 1971, there were 14 experimental weather modification projects in the region, many funded by federal funds (Skywater, 1972). Of the five states, South Dakota is the only one with a statewide program. Initial legislation was first passed in 1953 creating a Weather Control Commission (SDCL 39). Amendments were made in 1971 to the law for statewide program using multi-county areas for support of local programs (Williams, 1973).

Planners of operational innovative programs, of which weather modification is an example, have recognized that decisions affecting the regulation and allocation of resources to support such programs are not always perceived by local citizens as being in their own, or their community's best interest. This suggests that management of innovative programs, whatever their nature, require more than decisions based on economic, political, or scientific necessities. Program managers must also have some knowledge and understanding of the client social system (that is, the needs, attitudes, desires, and commitment of people to such programs in areas where they are initiated). Because seeding districts are seldom homogeneous, conflicts may arise between various groups whose goals are dissimilar. Program planners have recognized that information about the human response to operational weather modification can be obtained through evaluative research. In the allocation of resources for support of operational weather modification projects, less than 3 percent of the total funds have been allocated to analyzing the human response to such programs.

The present research study used the evaluative research design as outlined by Suchman, (1966, 39) in order to determine the presence or absence of a social problem, in terms of the human response to such programs. By providing a base line, change could be measured at later time periods. The research project was designed to answer the following questions:

1. What are the attitudes of residents toward weather modification programs? Are they in agreement or disagreement with such programs?

2. Do residents vary in their attitudes according to selected social and situational factors such as age, education, self concept, social, personal, and situational factors? Knowledge? Do residents vary in their attitudes according to social, cognitive, personal, and affective factors?

3. What factors can explain the most as to why attitudes vary from one citizen to the other?

II Review of Literature, Conceptual Model, Development of Hypotheses

Some consensus seems to be reached in the literature that attitudes can be defined as predispositions to act toward some social object when confronted by a certain stimulus (Oppenheirmer,1966, 106, Sherif, 1958, Krech, Crutchfield, and Ballachey, 1962, 137). Attitudes vary in intensity and duration. Attitudes do not exist in isolation; they differ over time as the actor responds to different situational and group norms. If attitudes of people are known,then it seems possible to make some prediction about their behavior. At least three components are suggested for attitude formation: (1) Cognition, the belief system behind the attitude; (2) Feeling, the intensity of attitude; (3) Affective or action component, i.e., what will be done because of the attitudes. Because attitudes are responses to abstract relationships, there is often a discrepancy between attitude and overt behavior.

A limited amount of research has been conducted concerning attitudes toward and perception of weather modification programs. Haas, Boggs, and Bonner (1971) reviewed research they had conducted in three different states, and found most residents were favorable toward the weather modification programs, there were few differences between target and non-target areas, acceptance was related to younger adults, those active in local politics, and persons with high levels of education. Few, if any, relationships existed between knowledge of the programs and information sources used, in fact residents had little knowledge of the programs. Some dissonance existed between groups whose goals were dissimilar, such as resort owners or tomatoe growers. Most residents believed local people should control the programs. Strodtbeck and DeSanti (1967) in a study of attitudes in an arid South Dakota community, observed that those with little knowledge of weather modification programs seemed to be less positive about such programs. Formal participation was positively related to weather modification programs, and most of the residents felt that because precipitation is highly variable anything that would increase rainfall was acceptable. Sewell and Day (1965) in a study of Canadian and U.S. residents found that non-farmers were more interested in weather modification programs, and residents favored more reliable weather forecasting models than cloud seeding. Bickert and Browne (1965) found that managers of 5 Colorado firms could not determine how much loss was due to weather, and weather problems did not enter into management decisions. Saarinen (1965) in a study of Great Plains residents found that acceptance of weather modification was related to acceptance of other agricultural innovations, younger farmers, and farmers completing more years of formal education.

Some generalizations seemed to be forthcoming from the various studies on attitudes. Attitudes are responsive to group norms. There is often a discrepancy between attitudes and overt behavior. Knowledge does influence attitudes (but some attitudes are built upon false knowledge or no knowledge). Most respondents have favorable attitudes toward science and weather modification programs. Whereas residents seek some inputs in the decision making process, many would doubt that such controls would rest with local residents. There may be some difference between residents of

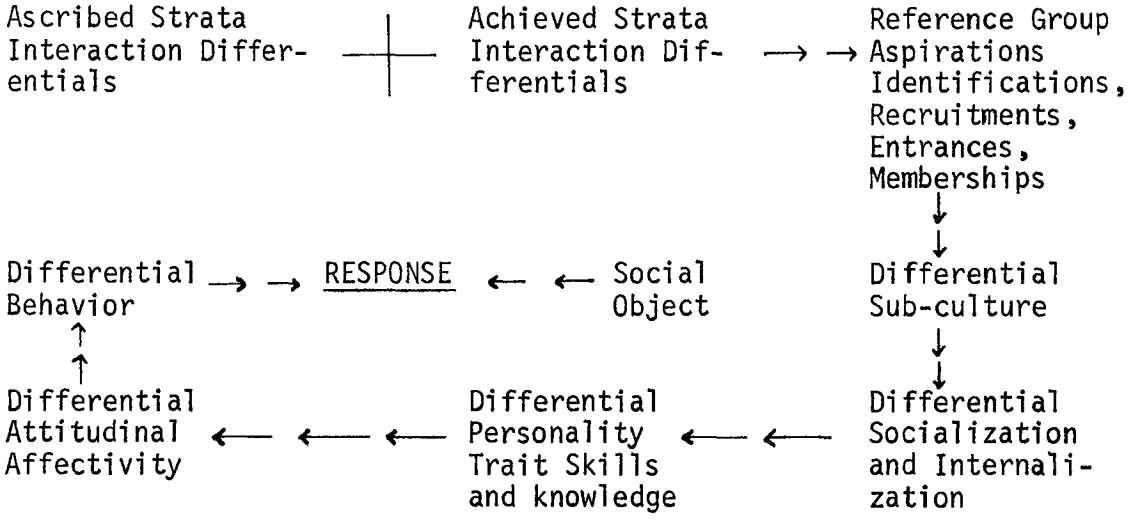
various categories such as resort operators, farmers and town residents in terms of acceptance of weather modification programs. Acceptance of weather modification is similar to the acceptance of other innovations in that age and education seem to be important explanatory variables.

Conceptual Model

The review of literature and the examination of some theoretical orientations generate a multivariate model that provides a profile for conceptualizing the relationship between selected social factors and attitude variation. As a configuration, the model might be diagrammed as portrayed in Figure 1.

Figure 1

Simplified Model on Attitude Formulation



The model illustrates that differences in a person's ascribed or achieved status rights are factors in the selection of one's reference groups which tend to create differential sub-cultures. These differential sub-cultures lead to variations in the education and socialization process which perpetuate variations in personality traits, skills and knowledge. These variations tend to shape one's attitude toward a stated social object which predisposes one to behave or act toward that social object in a preferential manner.

The following hypotheses were developed for the study.

1. Attitudes of local residents will be favorable to operational weather modification programs.

2. The greater the age of the respondent and the less the number of years of formal schooling completed, the less favorable the attitude toward weather modification programs.

3. The greater the population density of the area, the less favorable the attitude toward weather modification.

4. The greater the use of communication channels, the more favorable the attitudes toward weather modification programs.

5. The greater the knowledge of weather modification programs, the more favorable the attitudes toward weather modification programs.

6. The higher the status of the respondent in terms of occupation, the more favorable the attitudes toward weather modification.

7. The greater the length of time residents lived in the area, the more favorable the attitudes toward weather modification programs.

8. Church affiliation is associated with the residents' willingness to support weather modification programs.

III Research Design

The research design for the project involved the development of a personal interview schedule to obtain the data, the selection of a systematic random sample of farm, small town, and urban heads of households in the target area, and development of variables for a multiple-variable statistical analysis to identify the relevant factors determining attitudes toward weather modification. Several scales and indices were developed for use in the study. An attitudinal scale was used to measure attitudes toward weather modification programs using a scale that had been used in previous sociological studies. A self perception scale was also designed from questions used in other studies. Little research had been done on the relationship between attitudes toward social objects and knowledge. For this study a knowledge scale was developed in order to assess the level of knowledge of each respondent.

Target area of the research was an eight county district in the North Central part of South Dakota, composed of the following counties: Campbell, Walworth, Potter, Edmunds, Faulk, Spink, Brown and Corson. Corson is the only county not in the District 3 of the state program. Corson was included to identify differences, if any, as this county had its own program in past years. Because this was a pilot study to develop the instrument, a 1 per cent sample was randomly selected. The sample of 170 heads of households was selected as follows:

1. Residents of the City of Aberdeen (only major city in 8 county area). n=75

2. Farm residents of the 8 counties listed. n=34.

3. Residents of the largest community (in most instances the county seat with exception of Campbell County) in the 7 counties. n=58.

A five page interview schedule was designed, and pre-tested with farm residents, residents of a small community, and a large urban community, all of which were outside the target area, but similar to the area. Minor changes were made in the organization of the schedule, and additions were made to the questions used in developing the knowledge scale for the study. The "self perception scale" used 6 items similar to the Srole Anomie scale, the "Attitudes toward Weather Modification Scale" was developed from 10 questions that had been previously used in sociological studies of weather modification. (Haas, et al. 1971 and Strodtbeck and DeSanti, 1967). The data for the study was collected in August of 1972 by personal interviews. One hundred and seventy persons were interviewed, but only 167 usable schedules were coded for processing as three respondents did not answer all of the necessary questions.

The Dependent Variable

Attitudes toward operational weather modification programs was the dependent variable in the study and was defined in the following manner. (1) An attitudinal pool of 10 questions, drawn from previous sociological studies of attitudes toward weather modification, with a 7 point Likert attitudinal response continuum. (2) A cumulative score was calculated for each respondent which was the sum of his responses to the individual questions. Range of possible scores was from 10-70, with low scores indicating positive agreement with operational weather modification programs.

Independent Variables

Nineteen independent variables, representing five factors were developed for the study. The variables in the factors are defined and were measured as follows:

Situational Factors. The research model indicated that where a person lives, and the number of years he has resided in the area, have an influence upon his attitudes toward weather modification. Direction of relationship is also indicated in the definition of the variable within the factor.

X1. Residence--City of Aberdeen residents. Measured by dichotomous dummy variable. Direction positive.

X2. Residence--Small Communities. Measured dichotomous dummy variable. Direction positive.

X3. Residence--Farm. Measured by dichotomous dummy variable. Direction positive.

X4. Length of Residence--Measured by number of years lived in the area. Direction positive.

Cognitive Factor. This factor measures level of knowledge, and feeling about weather modification projects. The review of literature, and the model indicated that attitudes are in part determined by knowledge or lack of knowledge, and feeling about whether something works or does not work.

X5. Level of Knowledge Scale. Measured by responses to 4 questions in the interview schedule that ascertained: knowledge of objectives of weather modification programs, knowledge of organizations and individuals involved in weather modification programs, and location of operational programs. Range of scores on the scale was from 0-13 based on questions. Direction positive.

X6. Belief that Cloud Seeding can Suppress Hail. Dichotomous dummy variable. Direction positive.

X7. Belief that Cloud Seeding can Increase Rain. Dichotomous dummy variable. Direction positive.

Communication Factor. This factor serves as a measure of the sources of information available to the individual. Both personal and impersonal sources are included. By interaction with other individuals, ideas and attitudes are reinforced. Impersonal sources serve to introduce new knowledge.

X8. Number of magazines and newspapers received. Total number as indicated on the interview schedule. Direction positive.

X9. Personal participation in voluntary organizations. A Chapin scale was used to measure degree and amount of participation in voluntary organizations. Direction positive.

Personal Factor. Attitudes may also develop from personal factors such as age, education, occupation and self perception, and religious preference.

X10. Protestant Religious Preference. Dichotomous dummy variable. Direction positive.

X11. Roman Catholic Religious Preference Dichotomous dummy variable. Direction positive.

X12. Occupation Blue Collar. Dichotomous dummy variable, based on Edwards Classification of craftsman, kindred, unskilled worker. Direction positive.

X13. Occupation, White Collar. Dichotomous dummy variable, based on Edwards Classification of clerical, sales, professional workers. Direction positive.

X14. Occupation, Farmer. Dichotomous dummy variable. Direction positive.

X15. Age. Age at last birthday. Direction negative.

X16. Education. Number of years of formal schooling completed. Direction positive.

X17. Self Perception Scale. Measured by a modified Srole Anomie scale of 5 questions. Low scores meaning more positive self perception. Direction positive, that is as self perception increases, attitudes be more favorable.

Affective Factor. The factor attempts to measure commitment of respondent, and members of his immediate reference group and his friends, to programs of weather modification that would be proposed for his area.

X18. Personal Support. Measured by 1-7 scale, with low score indicating strong support for Weather Modification Programs, a high score for strong opposition. Relationship here positive. That is strong support would also mean more favorable attitudes.

X19. Support--Friends. Measured 1-7 scale. Low score strong support. Direction positive.

Statistical Analysis. The research study used Multiple Regression statistical technique as a method of determining the amount of explained variation in the dependent variable that was accounted for by all the independent variables acting together. (Blalock, 1960:326). The computer program used a step-wise analysis to isolate independent variables that were significantly related to the dependent variable. Level of significance established was .05. Several of the independent variables were "dummy variables". This is a statistical technique whereby qualitative data can be used if it is quantified with dichotomous categories.

Research Findings

This section contains the descriptive findings of the research. Tables are presented with the relationships identified in each of the three sub-sample areas, along with a summary of the findings for each table. The general agreement or disagreement on weather modification programs table reduces the quantifable scores on the index to strongly agree to strongly disagree continuum. Scores were aggregated as follows: Strongly Agree 10-15, Somewhat Agree 16-25, Agree 26-35, Uncertain 36-45, Disagree46-55, Somewhat Disagree 56-65, Strongly Disagree 66-70. The researchers assume that the midpoint represents an uncertain type of response pattern, and that the present scaling technology is not able to identify with certainty, in any of the methods used, the true mid-points for uncertain responses.

A general summary of the descriptive findings is included for the three sub-groups with the statistical findings.

TOPIC DESIGNATION: General Attitudes About Science and Changing the Weather

Stimulus Statement: Composite Scores of Attidues about Science and Changing the Weather

TABLE 1

CONCEPTUALIZATION OF WEATHER MODIFICATION PROGRAMS IN S.D.

Attitudinal Response	Farm		Small Town		City	
	Number	Percent	Number	Percent	Number	Percent
Strongly Agree	-	-	-	-	-	-
Agree	9	12.00	6	17.64	13	21.67
Mildly Agree	46	61.33	23	67.64	35	58.33
Undecided	18	24.00	4	11.76	11	18.33
Mildly Desagree	2	2.66	-	-	-	-
Disagree	-	-	1	2.94	1	1.67
Strongly Disagree	-	-	-	-	-	-
Total	75	100.00	34	100.00	58	100.00

A majority of residents from each of the three sections are in agreement with weather modification programs in South Dakota. The tendency, however, is to only mildly agree. Sixty-one percent of the farm residents, sixty-eight percent of the small town residents, and fifty-eight percent of the city residents gave a mildly agree response. Quite a few respondents were also undecided in their opinion. Nearly one-fourth of the farm residents, one-eighth of the small town residents, and one-fifth of the city residents gave an undecided response.

TOPIC DESIGNATION: Affective Committment to Weather Modification

Stimulus Statement: Do you think cloud seeding works: That is, can it actually increase moisture?

TABLE 2

DOES CLOUD SEEDING INCREASE MOISTURE?

Attitudinal Response	Farm		Small Town		City	
	Number	Percent	Number	Percent	Number	Percent
Yes	47	62.67	22	64.71	30	50.85
No	6	8.00	3	8.82	5	8.47
Uncertain	22	29.33	9	26.47	24	40.68
Total	75	100.00	34	100.00	58	100.00

A small majority of all three residential groups felt that cloud seeding does work. The percentages were: farm residents, sixty-three percent; small town residents, sixty-five percent; and city residents, fifty-one percent. A large percent of the city residents, forty-one percent, were uncertain as to whether or not cloud seeding works. Twenty-nine percent of the farm residents and twenty-six percent of the small town residents were also uncertain as to its effectiveness.

TOPIC DESIGNATION: Affective Committment to Weather Modification

Stimulus Statement: Do you think cloud seeding can suppress hail?

TABLE 3

DOES CLOUD SEEDING SUPPRESS HAIL?

Attitudinal Response	Farm		Small Town		City	
	Number	Percent	Number	Percent	Number	Percent
Yes	19	25.33	15	44.12	14	23.73
No	11	14.67	2	5.88	11	18.64
Uncertain	45	60.00	17	50.00	34	57.63
Total	75	100.00	34	100.00	58	100.00

The largest percent of all three groups were uncertain as to whether or not cloud seeding could suppress hail. The percentages were: farm residents, sixty percent; small town residents, fifty percent; and city residents, fifty-eight percent. Of the remaining respondents in each group, more people felt that cloud seeding could suppress hail than people who felt that it could not.

TOPIC DESIGNATION: Affective Committment to Weather Modification

Stimulus Statement: Who do you think should make the decision whether or not a cloud-seeding program should be allowed in your area?

TABLE 4

WHO SHOULD DECIDE TO ALLOW A CLOUD-SEEDING PROGRAM?

Attitudinal Response	Farm		Small Town		City	
	Number	Percent	Number	Percent	Number	Percent
Scientists Conducting the Program in S.D.	5	6.76	2	5.88	-	-
Federal Government	8	10.81	3	8.82	3	5.17
State Government	12	16.22	6	17.65	7	12.07
County Government	7	9.46	5	14.71	2	3.45
County and State Governments	12	16.22	3	8.82	5	8.62
Local Government	2	2.70	-	-	6	10.34
Local Residents	21	28.37	14	41.18	26	44.83
Scientists and State Government	7	9.46	1	2.94	9	15.52
Total	75	100.00	34	100.00	58	100.00

The largest percent of respondents from each of the three groups felt that the local residents should be able to make the decision whether or not to seed the clouds. The second largest percent of respondents in each category delegated the decision making to various groups; farm residents delegated state government and county and state governments, small town residents delegated state government, and city residents delegated scientists and state government.

TOPIC DESIGNATION: Affective Committment to Weather Modification

Stimulus Statement: If residents in your area were to vote on whether a cloud-seeding program to increase moisture and suppress hail should be permitted in your community, or nearby, how do you think you would vote?

TABLE 5

HOW WOULD YOU VOTE?

Attitudinal Response	Farm		Small Town		City	
	Number	Percent	Number	Percent	Number	Percent
For	52	69.34	19	55.88	44	74.58
Uncertain	12	16.00	7	20.59	4	6.78
Against	10	13.33	8	23.53	11	18.64
Wouldn't Vote	1	1.33	-	-	-	-
Total	75	100.00	34	100.00	58	100.00

Three-fourths of the city residents felt that they would vote for a cloud-seeding program. Sixty-nine percent of the farm residents and fifty-six percent of the small town residents also felt that they would vote for such a program. The small town residents, in comparison to farm and city residents, had the highest percentage of responses in the uncertain and against categories.

TOPIC DESIGNATION: Affective Committment to Weather Modification

Stimulus Statement: How do you think your friends would vote regarding a cloud-seeding program?

TABLE 6

HOW WOULD YOUR FRIENDS VOTE ON A CLOUD-SEEDING PROGRAM?

Attitudinal Response	Farm		Small Town		City	
	Number	Percent	Number	Percent	Number	Percent
For	31	41.33	16	47.06	23	38.98
Uncertain	34	45.34	9	26.47	18	30.51
Against	9	12.00	9	26.47	18	30.51
Wouldn't Vote	1	1.33	-	-	-	-
Total	75	100.00	34	100.00	58	100.00

The largest percent of farm residents, forty-five percent, were uncertain as to how their friends would vote. The largest percent of small town residents, forty-seven percent, and city residents, thirty-nine percent felt that their friends would vote for the program. More city residents, in comparison to the other two groups, felt that their friends would vote against the program. Only twelve percent of the farm residents felt that their friends would vote against it.

Statistical Findings

This section of the study reports the statistical analysis, and identifies variables relevant to the dependent variable following the step-wise regression program.

The null hypothesis developed for the study was:

No relationship will be found to exist between a set of independent variables representing Personal, Cognitive, Situational, Communication, and Affective Factors and the dependent variable, Attitudes Toward Weather Modification. Level of significance was established at .05.

The 19 independent variables account for 46.7 per cent of the explained variation in the dependent variable, Attitudes Toward Weather Modification. When subjected to the step-wise analysis, only 4 remained, accounting for 43.9 per cent of the explained variation in the dependent variable. Thus, the null hypothesis was rejected. However, it is interesting to observe that 15 of the variables did not attain significance, and accounted for only 2.8 per cent of the explained variation. Six of the fifteen variables accounted for little, if any, of that 2.8 per cent of explained variation when the print outs are analyzed.

Regression Equation

The regression equation is as follows, where: X18 Personal Support, X15 Age, X5 Knowledge, and X19 Support Friends.

$$Y = 17.26988 + 2.30234\ X18 + 0.09855\ X15 + (-)\ 0.045129\ X5$$

$$0.09433\ X19$$

The following table describes the amount of Sum of Squares Reduced, and Cumulative Proportion Reduced by each of the 4 variables.

TABLE 7

Analysis of Sum of Squares Reduced and Cumulative Proportion Explained

Variable	Sum of Squares Reduced	Cumulative Proportion
X18 Personal Support	2356.957	.349
X15 Age	279.832	.391
X5 Knowledge	196.646	.420
X19 Support-Friends	130.383	.439

V Discussion -- Summary and Conclusions

The research design used a multiple variable analysis to determine the relationship between several variables and attitudes toward weather modification program. A step-wise option enabled the researchers to delete variables that accounted for little, if any, of the explained variation in the dependent variable. This was accomplished without a loss of statistical significance. Four of the 19 variables attained significance, accounted for 43 per cent of the explained variation in the Attitudes Toward Weather Modification Scale. The null hypotheses was rejected.

Age was anticipated to have a negative relationship. Older persons reject new ideas and innovations because their primary socialization occurred at a different time period. The old is more familiar, the new involves a risk. The variable ranked 2nd of 4th in explanatory and/or predictive power.

Support for weather modification programs by the respondent and his friends ranked 1st and 4th. If a program were initiated at the local level to modify the weather, and if the respondent strongly supported such a program, he should have positive attitudes toward the program. This same anticipated relationships would exist in the perception of how his friends feel about the program. This variable ranked 1st (personal support), and 4th (perception of how friends feel) in the analysis. Analysis supports research attitudes built upon personal and group norms (Sherif, 1958).

Knowledge. Little research has been done on the relationship between knowledge and attitudes. Some attitudes are built upon false knowledge, or no knowledge. In this study, knowledge ranked 3rd in explanatory/predictivepower. The more knowledge, the more favorable the attitude. However, the level of knowledge was low for the entire sample. Mean score was 2.79, with standard deviation of 2.31. The numerical possible range on the scale was from 0 - 13. The researchers attempted to discern the level of knowledge about Weather Modification programs at the beginning of the schedule to avoid reactive influence.

Further Research is suggested by this study as there are several unanswered questions. The objectives were to determine attitudes toward weather modification, and isolate significant factors influencing such attitudes. Attitudes were favorable to weather modification programs. These attitudes were related to committment to a program by the resident, his perception of the committment of his friends, age, and knowledge. Mean attitude score was 30.44, with a standard deviation of 6.37. This places the average respondent in the agree category. Though small, the sample seemed representative of the area. As this was a pilot study to test the instrument used and research model, a much larger sample should be used in another study.

The researchers suggested changes in some of the indices used in the study. A scale should be developed to measure the affective component, the committment of the resident. Such a scale should have as some of its components the degree to which local control is desired, amount of tax

money to be committed to the programs, how they would vote if the issue is put on a referendum, and their perception of the support of their friends and neighbors. In the present study single indicators were used, and the suggestion is to build a composite index. Another question that needs some research is how residents receive messages about weather modification programs. The level of knowledge was very low in this study, and the researchers would hypothesize that the same phenomena would occur in other areas if they were studied. Do residents receive more information from their friends, or the mass media? Or, are there influential leaders in the areas that mold opinions and circulate information? (Katz, Levin, and Hamilton, 1963). In this study information sources were aggregated to form an information index.

How do residents feel about inter-state cooperation in weather modification programs? A preliminary analysis of existing legal statutes in the five state area suggest different legal norms for regulation and implementation of such programs. Future precipitation management programs in the Great Plains are based upon some form of inter-state cooperation.

Is consensus easier to achieve through a budget hearing, or public referendum? Some counties initiate the programs through budget hearings, others by ballot. The researches wonder if there are differences in attitudes when these controls are added. Another factor is the performance of past programs in determining attitudes. In one county, the commissioners put the issue to the voters on the November, 1972 ballot. The program was defeated by a 51-49 per cent margin. This county had previously been involved in an operational program. An analysis of the data from this study indicated that residents favored the program by a 7 - 2 margin (there were 9 in the random sample from this county). However, when the data was checked to find how they felt their friends would vote, the margin dropped to 4 for, and 5 against the program. In analyzing findings, the research literature reviewed suggested that in many instances, controversies develop over specific events, or over different personalities, and these are more crucial in determining a vote for a program than selected socio-economic characteristics of a community (Gamson and Irons, 1961).

The researchers suggested that further studies be initiated to check the reliability of the attitudinal scale as it is used with different samples. One other study in the region is now using the scale, and the researchers will compare results. As this was a bench mark study, additional research is needed to determine any attitudinal changes when operational programs are initiated.

ACKNOWLEDGEMENTS

The authors are indebted to Mr. Merlin Williams, director of the South Dakota Weather Control Commission for his encouragement and support of the research. The study was made possible by a grant from the Weather Control Commission to the Department of Rural Sociology and the Agricultural Experiment Station of South Dakota State University, and is one of a series of studies supported by the Weather Control Commission through Contract No. 14-06-D-7240 with the Division of Atmospheric Water Resources Management, Bureau of Reclamation.

Several others have also contributed to the research, and the authors express their appreciation to them. To Dr. Richard Rudel, Dr. W. Lee Tucker, Dr. Robert Wagner, and Dr. Robert Dimit, of South Dakota State University for their suggestions in developing the research instrument and statistical analysis; to Dr. Eugene Haas of the University of Colorado for his counsel at several stages in the study; to Mr. Philip Dwight and Dr. Russel Brock of Northern State College, Aberdeen for their support in the employment of interviewers; to Miss Annete Schumaker, Mrs. Marilou Molseed, Mr. Charles Bates, Mr. Ryland Sorenson, and Mr. Dan Salem, students in Sociology at Northern State College for their work as interviewers.

Appreciation is extended to Miss Karen Alickson for typing and compiling the tables, and to Mrs. Mary Ellen Hornstra, graduate assistant in Rural Sociology for her work in checking the tables and interpretation of the data.

- - - - -

REFERENCES

Blalock, Hubert. Social Statistics. New York: McGraw Hill.

Crutchfield, James A. - "Investment in Weather Modification Research: Objectives, Incentives and Applications," Human Dimensions of Weather Modification, Derrick Sewell, editor. Chicago: University of Chicago, Department of Geography, Research Report 105, 1966, pp. 363-373.

Festinger, Leon. A Theory of Cognitive Dissonance. Evanston: Row Peterson, 1957.

Gamson, William A. and Peter H. Irons. "Community Characteristics and Flouridation Outcome," Journal of Social Issues, Vol. XVII, No. 4, 1961, pp. 66-74.

Gannon, R. "Rain Made to Order," Popular Science Monthly, Vol. CXCIX, September, 1971, pp. 49-51+.

Garrison, W. L. "Evaluation of Weather and Climate by Socio-Economic Sensitivity Indices," Human Dimensions of Weather Modification, Derrick Sewell, editor. Chicago: University of Chicago, Department of Geography, Research Report 105, 1966, pp. 91-110.

Halpern, Richard S. "Some Observations about Attitudes, Attitude Measurement and Behavior," Attitude Research on Rocks, Lee Adler and Irving Crespi, editors. Chicago: American Marketing Association, 1968, pp. 38-45.

Haas, J. Eugene, Keith S. Boggs, and E. J. Bonner. "Science, Technology and the Public: The Case of Planned Weather Modification," Social Behavior, Natural Resources and the Environment, William Burch, Neil Chook and Lee Taylor, editors. New York: Harper and Row, 1971.

Haas, J. Eugene, Keith S. Boggs, and E. J. Bonner. "Science, Technology and the Public: The Case of Planned Weather Modification," unpublished paper presented at the session on "Society and its Physical Environment," at the annual meeting of the American Sociological Association, Denver, Colorado, August, 1967.

Job, For Modern Man. New York: American Bible Society, 1971.

Katz, Elihn, Martin L. Levin, and Herbert Hamilton. "Traditions of Research in the Diffusion of Innovations," American Sociological Review, XXVIII, April, 1963, pp. 240-241.

National Science Foundation. Human Dimensions of the Atmosphere. Washington, D.C.: National Science Foundation, 1968.

National Science Foundation. Weather Modification, Tenth Annual Report. Washington, D.C.: National Science Foundation, 1968.

Nolan, Michael, Robert Bealer and Vernon Ryan. "The Congruence in Sociological Research and Certain Guiding Theoretical Assumptions," unpublished paper presented at the annual meeting of the Rural Sociological Society, San Francisco, 1967.

Oppenheim, A. N. Questionnaire Design and Attitude Measurement. New York: Basic Books, 1966.

Roberts, W. O. "We're Doing Something About the Weather?" National Geographic, Vol. CXLI, April 1972, pp. 518-555.

Saarinen, T. F. "Attitudes Toward Weather Modification: A Study of Great Plains Farmers," Human Dimensions of Weather Modification, Derrick Sewell, editor. Chicago: University of Chicago, Department of Geography, Research Report 105, 1966, pp. 323-328.

Sewell, W. Derrick, (ed.). Human Dimensions of Weather Modification. Chicago: University of Chicago, Department of Geography, Research Report 105, 1966.

Sherif, Muzafer. "Group Influences Upon the Foundation of Norms and Attitudes," Readings in Social Psychology, Maccoby, Maccoby and Hartley, editors. New York: Holt, Rinehart and Winston, 1958, pp. 219-232.

Strodtbeck, Fred L. and Marie DeSanti. "A Study of Attitudes Toward Weather Modification, the Project Hailswath Case," Chicago: University of Chicago, Social Psychological Laboratory, June 1967.

Suchman, Edward A. Evaluative Research. New York: Russel Sage Foundation, 1967.

Von Bickert, Carl E. and Theodore D. Browne. "Perception of the Effects of Weather on Manufacturing: A Study of Five Firms," Human Dimensions of Weather Modification, Derrick Sewell, editor. Chicago, University of Chicago, Department of Geography, Research Report 105, 1966, pp. 307-322.

Williams, Merlin C. "South Dakota Weather Modification Program," ASCE Water Resources Engineering meeting, January 29-February 2, 1973, at Washington, D.C. Meeting Reprint 1883.

APPLYING ULTRA LONG RANGE WEATHER PREDICTION AND WEATHER MODIFICATION TO ENVIRONMENTAL MANAGEMENT

Irving P. Krick

American Institute of Aerological Research
Palm Springs, California 92262

ABSTRACT

Forty years of research, development and application in weather prediction and weather modification have been brought to bear on certain aspects of environmental management. A predicted drought, causing heavy crop losses in Oklahoma and adjacent areas in 1971 and early 1972, resulted in the combined use of these two technologies to overcome it.

At present many cloudseeding programs under the author's supervision are in force in western and north central Oklahoma. Drought has been eliminated in these areas, but continues at moderate to severe levels in the remainder of the state. Rainfall patterns within the various operating projects exhibit maxima in relation to outside areas. Economic benefits are measured by increases in water storage at municipal reservoirs and improved crop and rangeland conditions.

The ultimate objective of the program is to stabilize the economy in those areas historically frequented by drought. It is believed such an achievement will encourage people to return to the land, will increase productivity and generally assist the United States in supplying food and fibre to an increasing world populace.

PROLOGUE

Since the beginning of recorded history, weather and climate have had a profound impact on human activity. Ancient civilizations in some areas of the world rose and fell in relation to cycles of drought. Indeed, in recent history the great exodus from Oklahoma and the old "Dust Bowl" during the early 30s was precipitated primarily by persistent drought. An understanding of the atmosphere and its manifestations is therefore fundamental to the solution of various environmental problems.

A recognition of this basic principle led the author and his associates at the California Institute of Technologyin the 30s and 40s to pursue studies directed toward extending weather prediction and finally weather modification so that a combination of these two techniques might ultimately be applied to various problems of environmental management. The atmosphere was recognized as Nature's most effective recycling mechanism. Masses of particulates and

various effluents can be removed through normal atmospheric processes, combining turbulent diffusion and precipitation mechanisms. These processes have been going on for centuries, other wise humanity would be buried in refuse at this stage in our evolution.

Problems of both air and water pollution may ultimately be alleviated to some extent by the procedures discussed herein, but perhaps even more fundamental is the attempt to normalize weather. This objective becomes particularly important in respect to rainfall patterns in areas characterized by major drought cycles. The socioeconomic impact of such a normalizing program is readily apparent. If one can stabilize rainfall in areas of marginal precipitation and periodic drought, farmers and ranchers will not suffer recurring losses of a drastic nature. Furthermore, such action may encourage people to return to the land. Vast areas can enjoy increased productivity, thus aiding the United States in supplying food and fibre to an increasing world populace.

This paper reviews one such project currently going forward. In the past 20 years similar work has been implemented in many areas of the world by the author and his associates. Our group has attained a unique position as a result of 40 years' research, development and application of both long range weather prediction and weather modification. This effort in all its ramifications has permitted the engineering and use of economically sound and viable environmental management procedures. The methodology used in preparing ultra long range weather predictions as a basis for planning weather modification operations has been reported on, as well as the weather modification techniques employed, in numerous scientific and technical publications over a span of many years. The project reviewed herein traces the work activated during 1972 in the State of Oklahoma to alleviate severe drought -- a project applicable in any of the High Plains states during similar weather regimes. It took 3 years to get the present effort underway. This slow start was due in part to factors responsible for earlier controversies surrounding both long range weather prediction and weather modification.

GENERAL ACCEPTANCE OF LONG RANGE WEATHER PREDICTION AND WEATHER MODIFICATION HAS BEEN SLOW

The programs currently in operation in Oklahoma more or less duplicate those which were in force by our company during the drought of the 50s. Unfortunately, in that era, cloudseeding was not generally held to be effective, either by most of the scientific community or those in government. The same was true of long range weather forecasting.

The ponderous nature of the government bureaucracy and the conservatism of many of the scientific organizations supported by government research thus have had an adverse impact on the evolution of weather modification and related scientific disciplines required for effective work. Efforts to improve weather prediction and to extend the time intervals covered first received criticism from these groups back in the 30s and 40s, with the advent of investigations of this nature at California Institute of Technology. When the military establishment in World War II wade effective use of Caltech's long

range forecasting techniques, well-organized efforts to discredit the work were mounted by some elements of the scientific community. As applications have continued to increase within the business community, attempts to deny the validity of such forecasts by those who have not been successful in this scientific field have increased in almost geometric proportion.

With the advent of weather modification concepts in the late 40s, government agencies and these same segments of the scientific community first took a position denying the possibilities of weather modification, and discouraged user groups from mounting operational programs. This had a disruptive impact, and deterred progress in the United States for over a decade, in spite of the fact that experimental work and operational successes were being reported worldwide. In 1966 the National Academy of Sciences validated the principles of cloudseeding and recommended large government appropriations to move it forward. Many millions of dollars have since been expended through government action but little clear evidence to support their results has been claimed. This is due in part to the lag in recognizing and developing sound long range forecasting procedures, which are an essential element in progressing and evaluating any large-scale regional or indeed global weather modification program. How can one attempt to normalize weather and balance the ecology before understanding and predicting the way in which natural weather events will evolve, -- a prerequisite to any well conceived weather modification program?

In our company's operation this principle was well established many years ago. It was considered hazardous to launch commercial operations without this background knowledge. Those who practice weather modification without adequate control data, in which predictions of the upcoming weather are inherent, can produce inadvertent effects, or arouse suspicion. For example, questions could be raised on the possible impact of massive cloud seeding of hurricane Debbie in 1969 over the Atlantic Ocean on subsequent floods downwind in Tunisia. There are those who suspect that residual silver iodide thrown up into the jet streams, which move from west to east around the globe, could have an effect in intensifying storms occurring over the Mediterranean and adjacent areas following these operations. Also, the seeding of hurricane Ginger in late September of 1971 off the south Atlantic Coast could be suspect, since it acted similarly to the one seeded by General Electric scientists in October of 1947. In each case the hurricane, which was expected to move out to sea, suddenly reversed its course and smashed into the East Coast. More recently, cloudseeding just prior to the Rapid City flood in South Dakota on June 9, 1972, has raised suspicions that these operations might have had an adverse effect on the evolving storm situation.

We have managed to avoid occurrences of this kind in our operations because we are privy to the possible effects of cloudseeding under various storm conditions as they evolve. All contracts include a clause which permits us to use our best professional judgment to suspend operations in any situation where we feel cloudseeding could be detrimental to our own clients or others adjacent to the operation. For example, in Louisiana, where operations each year are progressed for the American Sugar Cane League to augment the crops, suspensions are ordered whenever hurricanes approach the Gulf Coast. By avoiding situations of this kind, our liability insurance coverage remains in force and any legal action that might arise can be effectively defended.

Furthermore, the local control of all of our operational projects by the user agencies insures the elimination of controversy where conflicts of interest could arise. For example, people harvesting crops in one area might not wish additional rainfall. Disputes of this kind are easily resolved by the board of directors of such projects because of the representation of all area-wide interests on that board. Instructions are issued to the operating company in response to resolutions adopted by those responsible to the various groups funding the effort.

Due to the long interval between the 50s and the present, during which weather modification remained more or less in limbo within the various government departments and much of the scientific community, those of us in the private sector who have moved forward continuously toward the obvious objectives of weather modification are now far in the lead. Our less progressive colleagues, recognizing this, are bombarding the public with propaganda which implies that experimentation must go forward for many years before operational programs of the type people want can be mounted. This does not take into consideration the work of the small nucleus of well-qualified scientists and engineers in the private sector who have been responsible for the progress achieved in both long range weather prediction and weather modification over the past several decades. To merely carry on experimental programs similar to those which have been repeated over and over since the late 40s would constitute an unnecessary regression for those of us who have passed far beyond these elementary exercises. Some of the government programs and those under contract to government with universities and portions of the private sector are considered by many to be wasteful and repetitive. Research in evaluating physical and economic benefits of cloudseeding and an attack on air and water pollution problems deserve priority at this stage.

Perhaps President Nixon's effort to return to the people many of the decision-making functions now intrenched in government will cause these inequities which in some cases are adverse to the public interests to surface, and corrective measures instituted.

BACKGROUND OF THE OKLAHOMA WEATHER MODIFICATION EFFORT

In the late 1960s the author was assigned the task of preparing weather and streamflow forecasts extending into the mid-1970s for an electric power company. This involved the study of relationships between the various global weather systems which are intimately coupled and led to the discovery of drought development in the old Dust Bowl areas of the Southwest. It was found that 1969 would be the last year of a wet cycle, that drought would set in by 1970 and cumulative deficiencies would become noticeable by 1971 and 1972.

For over two decades the FARMER-STOCKMAN, a monthly magazine published in Oklahoma, Texas and Kansas, had carried our long range weather forecasts each month. In the October 1969 issue we warned of upcoming drought in the years ahead, particularly affecting Oklahoma and west Texas. Although deficiencies in rainfall began to accumulate in 1970, moisture reserved had been quite adequate and no great attention was given to these predictions. However, by the spring of 1971 substantial losses, estimated to amount to around

$250,000,000, were sustained by wheat farmers in Oklahoma alone. By April of 1971 the situation had gained widespread attention, and the FARMER-STOCKMAN published a follow-up review of the October 1969 article, simply confirming the fact that the forecast had been validated. Farmers and ranchers were urged to give consideration to the reestablishment of cloudseeding programs which had been successful in Oklahoma and Texas during the drought of the 50s.

Sufficient interest was stimulated to prompt Governor Hall of Oklahoma, in July of 1971, to establish a broad-based 14 member Study Committee on Weather Modification, chaired by Mr. Ferdie Deering, Editor-Manager of the FARMER-STOCKMAN. This group recommended widespread cloudseeding operations in an effort to stem the drought. Simultaneously, the United States Bureau of Reclamation instituted an experimental program in southwestern Oklahoma but no operational work was funded that year.

In October of 1971 a regional meeting on the subject was convened in Oklahoma City at Governor Hall's request. It was attended by interested groups from about 11 states, and Mexico. Plans were initiated for the establishment of regional weather modification efforts to control future droughts.

By the spring of 1972, with the recurrence of drought characterized by less than an inch of rain in southwestern Oklahoma between January 1st and April 1st, many groups began to agitate for operational programs in addition to experimental work. The first such project was instituted by the City of Lawton, where municipal reservoir storage had diminished to seriously low levels. The pumping of water from an upstream lake to the storage area where the municipal purification system was located had become impossible for a period of 60 days because of low water conditions. On April 5th the City Council of Lawton held an emergency session with the author to determine the feasibility of reinstating cloudseeding programs which had been operated for that city in the 50s and 60s. Forecasts were presented to the Council indicating that an early authorization would permit operations of an effective nature between April 18th and 21st and again about April 26th. The Council accepted these forecasts at face value, and executed a one-year contract on April 11th.

THE LAWTON STORY

The storm predicted for the interval between the 18th and 21st, with cloud seeding operations in full force, yielded up to about 2 inches of rainfall, thus beginning to prepare the desiccated watershed area so that eventually some runoff could be achieved. On April 26th and 27th rainfall amounts up to 4½ inches occurred in the Lawton watershed area. National Weather Service data for the month of April clearly delineated an area of maximum rainfall statewide for the month in the Lawton watershed, despite the fact that normals in Oklahoma increase sharply from west to east. By May 1st over 3 billion gallons of water had flowed into the Lawton reservoirs, and pumping from the prime source to the municipal water supply area was resumed. Fringe benefits were received throughout the farming community in the Lawton watershed; crops responded to the rainfall, and stock ponds were filled. The Lawton reservoirs have received additional storage water as the project continues.

Figures 1 and 2 depict the rainfall patterns in inches both inside and outside the watersheds involved for the storm periods referred to. On Figures 1 and 2 the operational logs are tabulated and the dispersion plumes from the active generators depicted, illustrating how the silver iodide traversed the distance from the ground up to the temperature level where it became effective. Figure 3 shows rainfall over the state in April, expressed as a percentage of the April normal. This chart was prepared by the National Weather Service at the request of the Oklahoma Farm Bureau. Added significance may be attributed to the chart when one considers the fact that cloudseeding effects were limited to the latter half of the period.

OTHER OKLAHOMA DEVELOPMENTS

The success of the Lawton operation in virtually turning around the drought spearheaded the establishment of other Oklahoma projects during the summer of 1972, the next being a contract with Oklahoma State University at Stillwater. The University and the City of Stillwater joined forces to try to improve storage in Lake Carl Blackwell, which supplies that city. Concurrently and during the subsequent months many projects in the Oklahoma Panhandle and other western counties as far south as the Texas border were activated. At present 11 projects are going forward in Oklahoma and others are contemplated where rainfall deficiencies continue in central and eastern parts of the state. (See Figure 4 and Table 1.)

A second regional weather modification conference was held recently in Dallas, Texas, sponsored by agencies of both Oklahoma and Texas, at which Governor Hall was the principal speaker. He urged action to implement operational programs over wide areas, and stressed the importance of applying the knowledge presently at hand to hold the line on drought during the upcoming years. Research efforts, of course, will continue to improve the effectiveness of all scientific disciplines which must be brought to bear on these problems.

OPERATIONAL PROCEDURES

Such environmental management programs by our company rely heavily upon a combination of ultra long range weather prediction and weather modification to establish effective procedures. We use our expertise in these fields to try to normalize weather conditions in project areas or in some instances to optimize rainfall regimes for various crops. These regimes differ with crops and seasons -- for example, cotton in Oklahoma requires abundant rain in summer, with August a critical month; winter wheat needs rain in September and October and again in March, April and May. The County Extension services are in a position to indicate optimum amounts of rainfall required in each county, by months, for each crop grown. Thus by understanding this relationship, a combination of long range weather prediction and estimated effects from weather modification operations can be used to provide farmers with an idea of crop expectations before they undertake a cloudseeding program.

IDENTIFIER	PROJECT NAME	STARTING DATE	AREA IN SQ. MI.	SILVER IODIDE GROUND GENERATOR OPERATIONAL HOURS						
				APR	MAY	JUN	JUL	AUG	SEP	TOTAL
OC-2	Lawton Watershed	14 Apr	225	274:30	420:30	303:15	325:00	416:30	192:30	1932:15
OC-3	Stillwater Watershed	10 May	144		164:00	278:00	415:30	406:45	276:30	1540:45
OC-4	Hitchland Ranch	21 May	64		43:30	116:00	242:00	218:00	91:00*	710:30
OC-5	Harper County	21 May	1034							
OC-6	Woodward County	10 Jun	1235		68:00	411:00	671:30	1050:30	520:15	2721:15
OC-7	Ellis County	1 Jul	1222							
OC-8	Beaver County	11 Jul	1793							
OC-9	Cotton County	1 Aug	629					318:45	225:00	543:45
OC-10	Custer County	13 Aug	999					228:30	218:45	447:15
	TOTAL		7345 Sq. Mi.					GRAND TOTAL		7448:30
			4,700,000 Acres							

*Program suspended 20 September because of wetness

Table 1

LOG OF AgI GROUND GENERATOR HOURS
FOR OKLAHOMA PROJECTS
APRIL THROUGH SEPTEMBER 1972

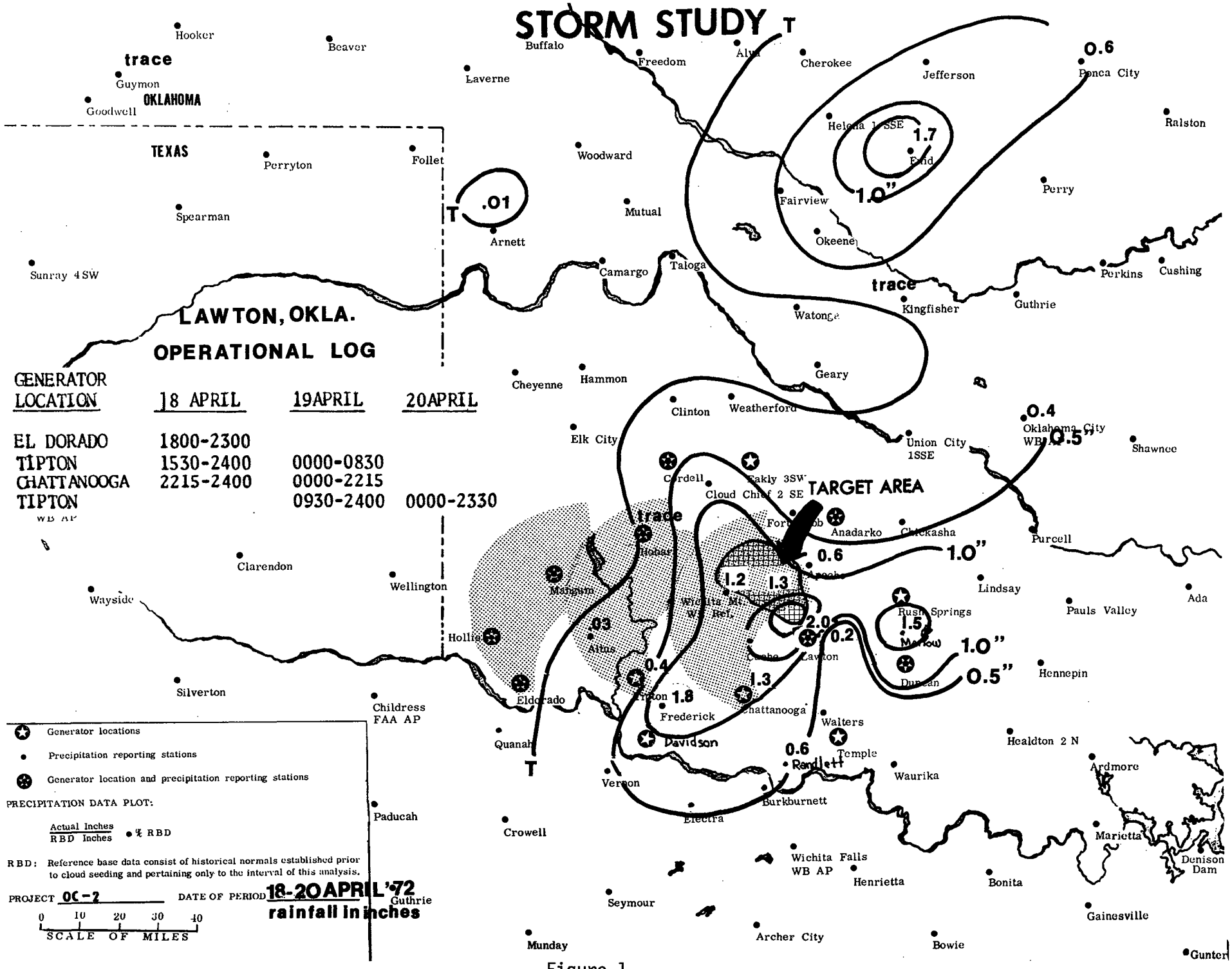

STORM STUDY
LAWTON, OKLA.
OPERATIONAL LOG
GENERATOR LOCATION | 18 APRIL | 19APRIL | 20APRIL
EL DORADO | 1800-2300
TIPTON | 1530-2400 | 0000-0830
CHATTANOOGA | 2215-2400 | 0000-2215
TIPTON WB AP | 0930-2400 | 0000-2330
TARGET AREA
Generator locations
Precipitation reporting stations
Generator location and precipitation reporting stations
PRECIPITATION DATA PLOT:
Actual Inches / RBD Inches • % RBD
RBD: Reference base data consist of historical normals established prior to cloud seeding and pertaining only to the interval of this analysis.
PROJECT OC-2
DATE OF PERIOD 18-20 APRIL '72
rainfall in inches
SCALE OF MILES
OKLAHOMA
TEXAS
trace
T
.01
0.6
1.7
1.0"
0.4
0.5"
1.2
1.3
2.0
0.2
1.5
1.0"
0.5"
0.03
0.4
1.3
1.8
0.6
Hooker
Beaver
Guymon
Goodwell
Buffalo
Freedom
Laverne
Alva
Cherokee
Jefferson
Ponca City
Ralston
Perryton
Follett
Woodward
Fairview
Perry
Spearman
Mutual
Arnett
Okeene
Sunray 4 SW
Camargo
Taloga
Perkins
Cushing
Kingfisher
Guthrie
Watonga
Cheyenne
Hammon
Geary
Clinton
Weatherford
Oklahoma City
Union City 1SSE
Shawnee
Elk City
Cordell
Cloud Chief 2 SE
Anadarko
Chickasha
Purcell
Clarendon
Wellington
Wayside
Mangum
Lindsay
Ada
Rush Springs
Pauls Valley
Hollis
Altus
Lawton
Duncan
Hennepin
Silverton
Childress FAA AP
Eldorado
Frederick
Chattanooga
Walters
Quanah
Davidson
Temple
Healdton 2 N
Vernon
Randlett
Waurika
Ardmore
Paducah
Electra
Burkburnett
Crowell
Marietta
Wichita Falls WB AP
Denison Dam
Henrietta
Bonita
Seymour
Gainesville
Munday
Archer City
Bowie
Gunter

Figure 1.

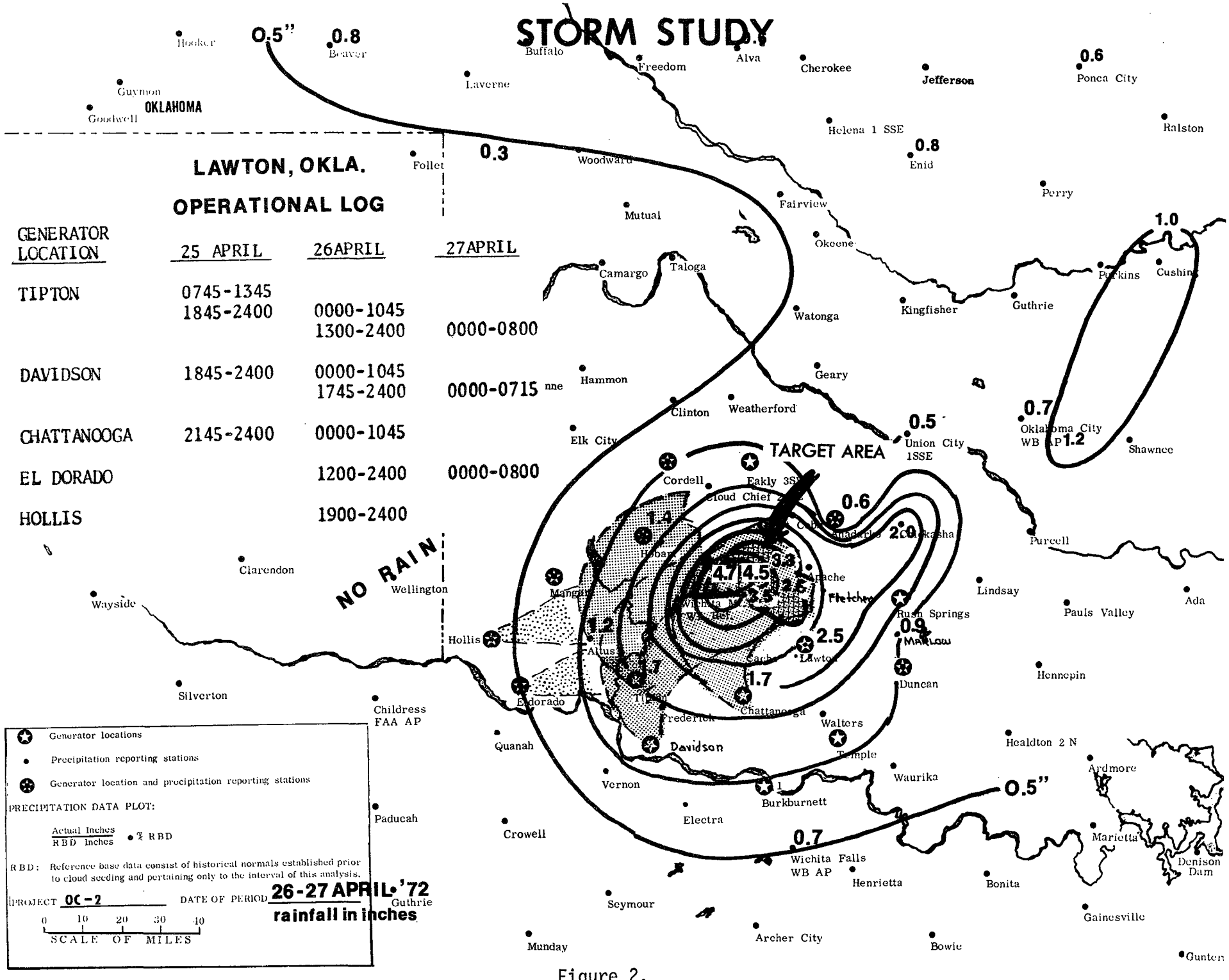

STORM STUDY
LAWTON, OKLA.
OPERATIONAL LOG
GENERATOR LOCATION | 25 APRIL | 26APRIL | 27APRIL
TIPTON | 0745-1345 1845-2400 | 0000-1045 1300-2400 | 0000-0800
DAVIDSON | 1845-2400 | 0000-1045 1745-2400 | 0000-0715
CHATTANOOGA | 2145-2400 | 0000-1045 |
EL DORADO | | 1200-2400 | 0000-0800
HOLLIS | | 1900-2400 |
TARGET AREA
NO RAIN
OKLAHOMA
Generator locations
Precipitation reporting stations
Generator location and precipitation reporting stations
PRECIPITATION DATA PLOT:
Actual Inches / RBD Inches • % RBD
RBD: Reference base data consist of historical normals established prior to cloud seeding and pertaining only to the interval of this analysis.
PROJECT OC-2
DATE OF PERIOD 26-27 APRIL '72
rainfall in inches
0 10 20 30 40
SCALE OF MILES

Figure 2.

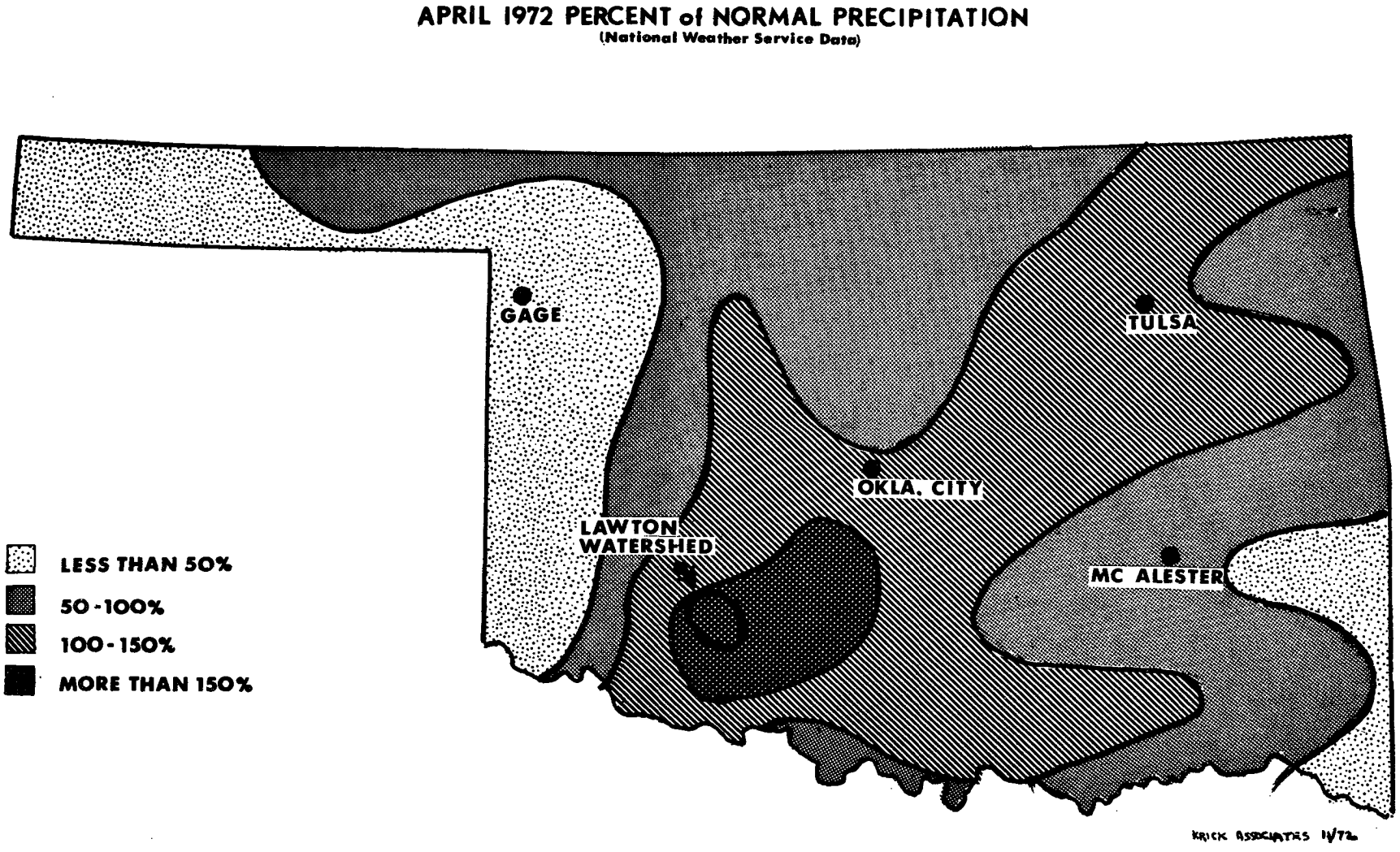

APRIL 1972 PERCENT of NORMAL PRECIPITATION
(National Weather Service Data)
GAGE
TULSA
OKLA. CITY
LAWTON
WATERSHED
MC ALESTER
LESS THAN 50%
50 - 100%
100 - 150%
MORE THAN 150%
KRICK ASSOCIATES IV/72

Figure 3.

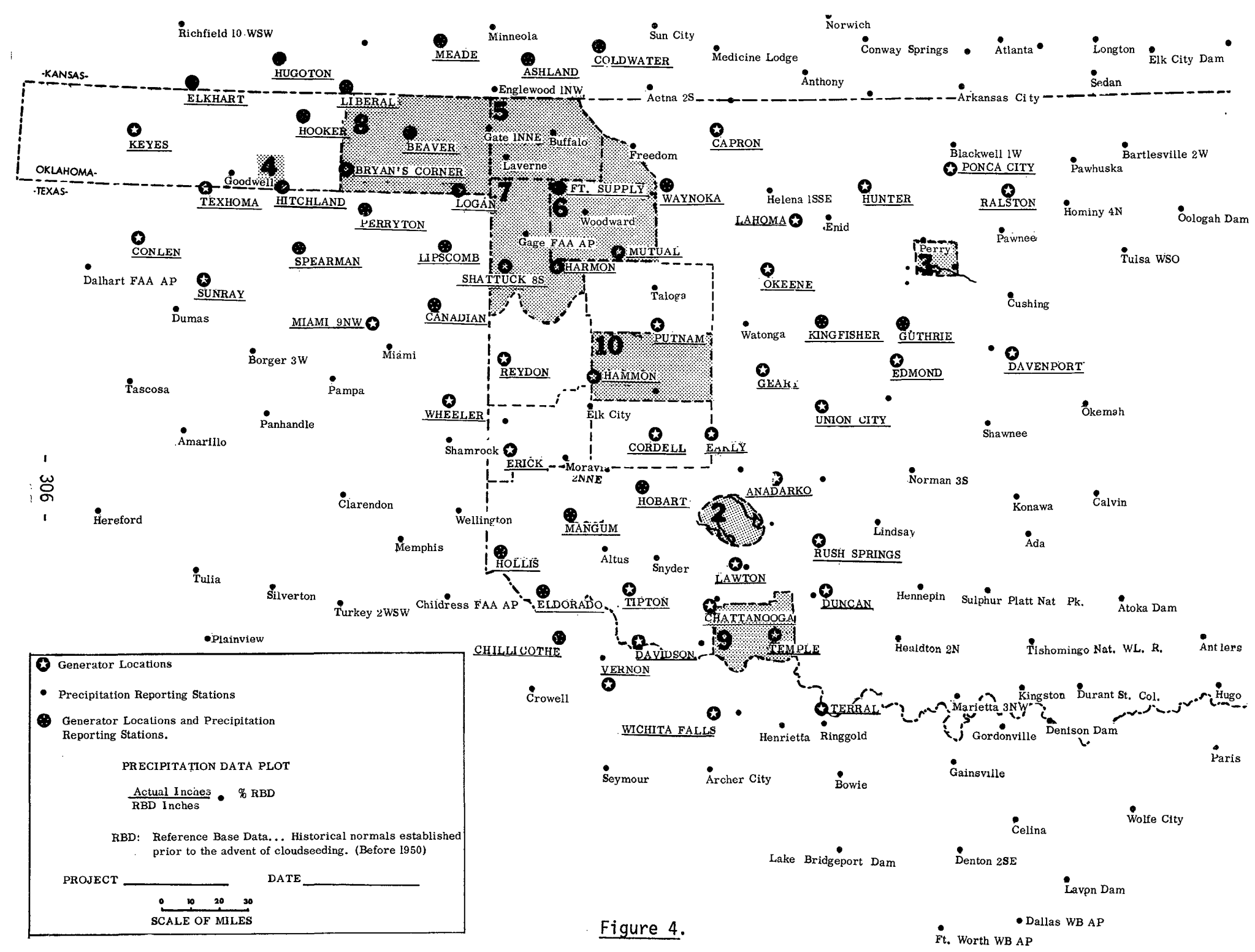

Richfield 10 WSW
Minneola
Sun City
Norwich
MEADE
COLDWATER
Medicine Lodge
Conway Springs
Atlanta
Longton
Elk City Dam
HUGOTON
ASHLAND
Anthony
Sedan
-KANSAS-
ELKHART
LIBERAL
Englewood 1NW
Actna 2S
Arkansas City
HOOKER
BEAVER
Gate 1NNE
Buffalo
CAPRON
KEYES
Freedom
Blackwell 1W
Bartlesville 2W
PONCA CITY
Pawhuska
OKLAHOMA-
-TEXAS-
Goodwell
Laverne
BRYAN'S CORNER
FT. SUPPLY
WAYNOKA
Helena 1SSE
HUNTER
RALSTON
Hominy 4N
Oologah Dam
TEXHOMA
HITCHLAND
LOGAN
PERRYTON
Woodward
LAHOMA
Enid
Pawnee
CONLEN
Gage FAA AP
MUTUAL
Perry
SPEARMAN
LIPSCOMB
HARMON
Tulsa WSO
Dalhart FAA AP
SUNRAY
SHATTUCK 8S
OKEENE
Taloga
Cushing
Dumas
CANADIAN
MIAMI 9NW
PUTNAM
Watonga
KINGFISHER
GUTHRIE
Borger 3W
Miami
REYDON
HAMMON
EDMOND
DAVENPORT
Tascosa
Pampa
GEARY
WHEELER
Elk City
UNION CITY
Okemah
Panhandle
Amarillo
Shamrock
CORDELL
EARLY
Shawnee
ERICK
Moravia 2NNE
Norman 3S
ANADARKO
Clarendon
HOBART
Konawa
Calvin
Hereford
Wellington
MANGUM
Lindsay
Ada
Memphis
RUSH SPRINGS
HOLLIS
Altus
Snyder
LAWTON
Tulia
Silverton
Childress FAA AP
ELDORADO
TIPTON
DUNCAN
Hennepin
Sulphur
Platt Nat Pk.
Atoka Dam
Turkey 2WSW
CHATTANOOGA
Plainview
CHILLICOTHE
DAVIDSON
TEMPLE
Healdton 2N
Tishomingo Nat. WL. R.
Antlers
VERNON
Crowell
Kingston
Durant St. Col.
Hugo
TERRAL
Marietta 3NW
WICHITA FALLS
Henrietta
Ringgold
Gordonville
Denison Dam
Paris
Seymour
Archer City
Bowie
Gainsville
Wolfe City
Celina
Lake Bridgeport Dam
Denton 2SE
Lavon Dam
Dallas WB AP
Ft. Worth WB AP
- 306 -
Generator Locations
Precipitation Reporting Stations
Generator Locations and Precipitation Reporting Stations.
PRECIPITATION DATA PLOT
Actual Inches / RBD Inches • % RBD
RBD: Reference Base Data... Historical normals established prior to the advent of cloudseeding. (Before 1950)
PROJECT
DATE
0 10 20 30
SCALE OF MILES

Figure 4.

Also, through a foreknowledge of upcoming weather events and their potential for useful cloudseeding operations, the ecology, and thus economic and social factors, can be stabilized. This is particularly important in areas of marginal rainfall such as the Great Plains, where periodic drought has always been a problem. Historically farmers and ranchers there have suffered crushing economic losses. By stabilizing the economy in these areas, not only can people be assured a steady income but many who have been reluctant to settle there may be encouraged to do so.

We maintain long and short range weather forecasting laboratories for the development of operational design and for calculating control data, so that dispersion patterns of cloudseeding material can be accurately computed continuously from ongoing surface and upper air information. This technique permits one to key the operational impact, either from single cloud formations or cloud bands associated with storm fronts, to specified target areas. Under generally similar airflow conditions and meteorological characteristics, it is possible to predetermine from historical data the required generator sites to use in seeding a given target when planning a project. All of these principles have been engineered to a viable, economically sound level by our company over a period of more than 20 years. They have been found effective when applied in all climatic zones to attack potential precipitation situations, be they airmass, orographic or frontal.

It is essential that cloudseeding controllers be experienced synoptic meteorologists. The performance of this function in our organization is restricted to personnel with at least 15 to 20 years' field experience. They in turn are under the supervision of executives with 30 to 40 years' background in the field of synoptic weather prediction and the application of such knowledge both inside and outside academia.

It cannot be emphasized too strongly that it is necessary to maintain a continuous vigil in order to actuate appropriate generators as the weather situation evolves. The long range forecast alerts cloudseeding controllers to the general period when cloudseeding operations may be initiated, but the hour-to-hour flow of surface and upper air data covering winds, temperatures and moisture is required for the computation of the dispersion patterns which will be effective in targeting rainfall to the particular watersheds or farm and ranch lands involved. These calculations determine the ground units which will be activated to produce the desired patterns. Cloudseeding controllers telephone instructions to the generator operators based on these data calculated at Palm Springs, where weather information is continually received over the government-operated weather communication system. These circuits transmit raw weather data as well as weather charts, radar maps of storm echoes and other material. The times specified by the controllers for operation of each generator are logged at Palm Springs and by the generator operators. These logs become a permanent record for use in reporting to regulatory bodies, in evaluation studies and for other purposes.

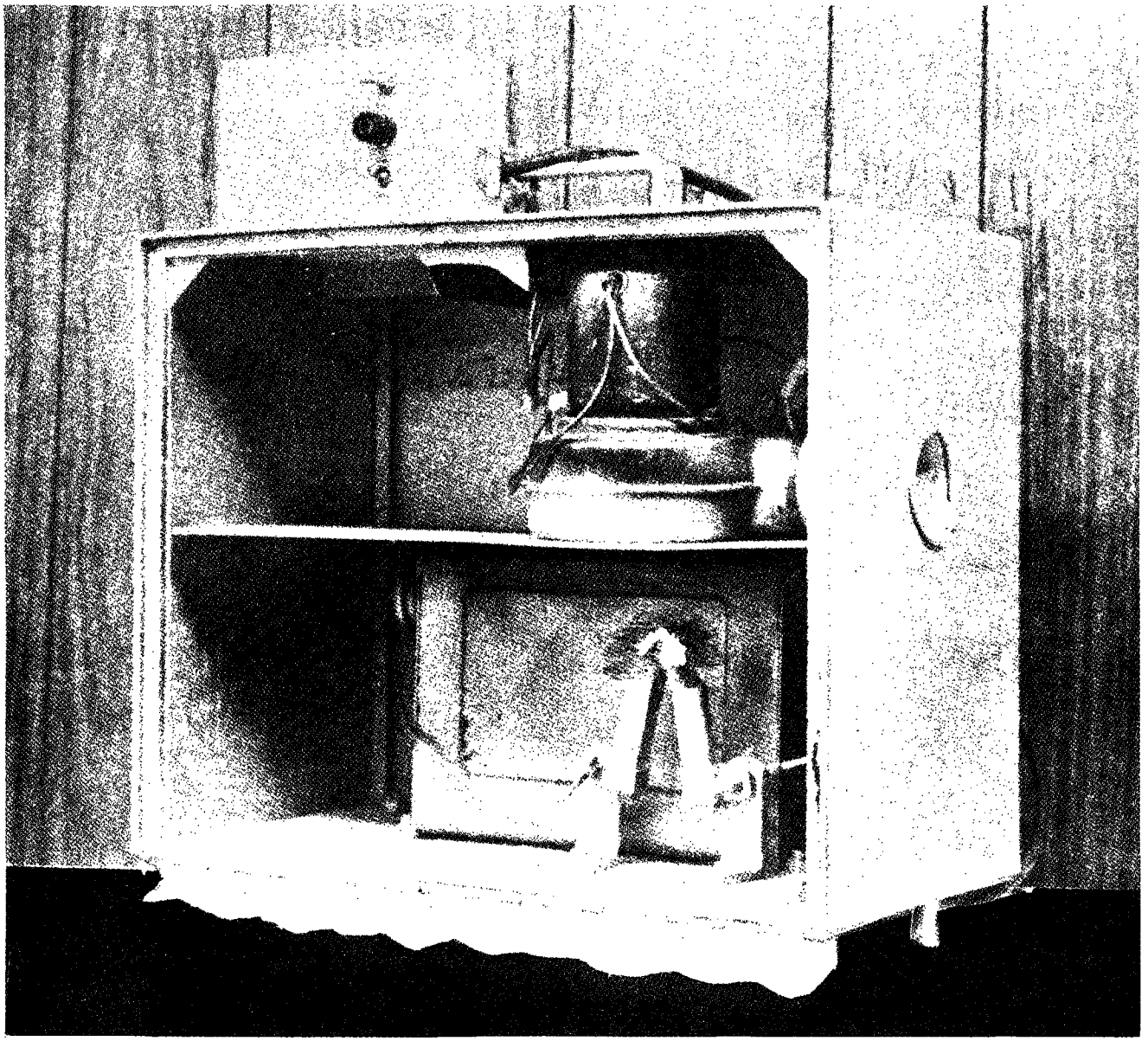
GIVING NATURE AN ASSIST

The operation of the ground-based cloudseeding system duplicates, insofar as possible, Nature's own rain-making processes. It has been found reliable under all weather conditions and extremely economical. The various nucleants available in Nature originate at ground level. Clouds are formed in rising air when moisture condenses on dust and other particles present in the wind streams. Unfortunately, in Nature the dispersion of such materials is sporadic, amounts are extremely variable and the different soils and substances acting as condensation and ice nuclei are frequently very inefficient in triggering natural rainfall. By controlling the output and distribution of ice nuclei, a cloudseeder can exert considerable influence over both the area where precipitation will develop and its character. It has been found that the spreading of silver iodide nuclei over a prospective target area some time in advance of the arrival of cloud systems to be seeded is most effective. This procedure is best achieved from ground-based units where continuous operation from fixed locations is possible. The output of the silver iodide generators is related to the positioning of the generator with respect to the target.

It has been found that with an output of 1/2 gram per hour, which yields 300,000 billion (3×10^{14}) ice nuclei per hour, from our particular arc type unit (see Plate 1), the optimum effects are achieved around 30 to 50 miles downwind from the generator, in the typical Oklahoma summer rainfall situations. Some readers may be surprised at the rather small amounts of silver iodide(AgI) vaporized, because most cloudseeders use many times this output. Our experience has shown that once the ice crystal process has been initiated within either a single cloud cell or cloud sheet, the entire system becomes charged with a multiplicity of ice crystals, sometimes thousands of times the numbers of ice nuclei injected originally into the airstreams. For this reason, only small amounts of AgI, properly dispersed continuously at the right time and place, have been found to be adequate.

The important point, particularly under changing wind conditions, as experienced when weather fronts pass across a target, is that the controller must be adept in altering the generators in use so as to take advantage of changing wind and temperature conditions while remaining on target. Only ground units afford this precise control. In airmass thunderstorms in summer without the passage of weather fronts, many times a steady state condition is achieved. In other words, all wind, temperature and moisture conditions remain constant during a rain period. Once the range from the generator to the target is properly established, outstanding results in both targeting and amounts of precipitation produced in relation to surrounding areas can be attained.

During the past 20 years, hundreds of cloudseeding projects in all climatic areas of the Free World have been completed by our company. As a result, quite effective estimates of performance levels to be achieved in connection with specific tasks can be established before initiating a program. This is accomplished by coordinating long range weather forecasts and weather modification capabilities with data related to water supply requirements or optimum rainfall amounts needed for crops and rangeland.



ARC-TYPE SILVER IODIDE DISPENSING GROUND GENERATOR
(MODEL 1730)

PLATE 1

ASSESSMENT OF RESULTS

In commercial cloudseeding the operator is expected to perform certain tasks, such as augmenting water supply, increasing crop yields and improving rangeland conditions. Frequently there is difficulty in measuring results from scattered rainfall reporting stations. Rainfall data must be supplemented by studies relating storage changes in reservoirs, crop and rangeland conditions, before and after operations, and other factors.

Figure 4 shows the various project areas reviewed herein as operated by ground-based equipment. The location of installations in Oklahoma, Kansas and Texas required to perform the tasks involved are indicated. Figure 5 is the drought map prepared by the National Weather Service and released on September 16, 1972. It can be seen that the project areas lie outside the areas of moderate to severe drought in Oklahoma. As previously mentioned, western Oklahoma was in severe drought from January to early April. This situation has changed during cloudseeding, but the remaining portions of the state have continued in drought.

In Figure 6 the principal rain-bearing airstreams overriding Oklahoma have been superimposed on Figure 5 both at ground levels and at heights where silver iodide becomes effective. Note that the wind at the effective seeding level parallels the straight line of demarcation between the wet areas of western Oklahoma and the dry areas to the south and east. This phenomenon may be interpreted as physical evidence of the effectiveness of the silver iodide plumes over our targets in Oklahoma. Also note that in other areas of the U.S. the line separating dry from wet areas is irregular in its configuration and thus rather random in nature. Following September 16th, the conditions depicted in Figure 5 have been improved in southwest Oklahoma. By the end of October sufficient rainfall had occurred to guarantee an abundant wheat crop for 1973 in the project areas.

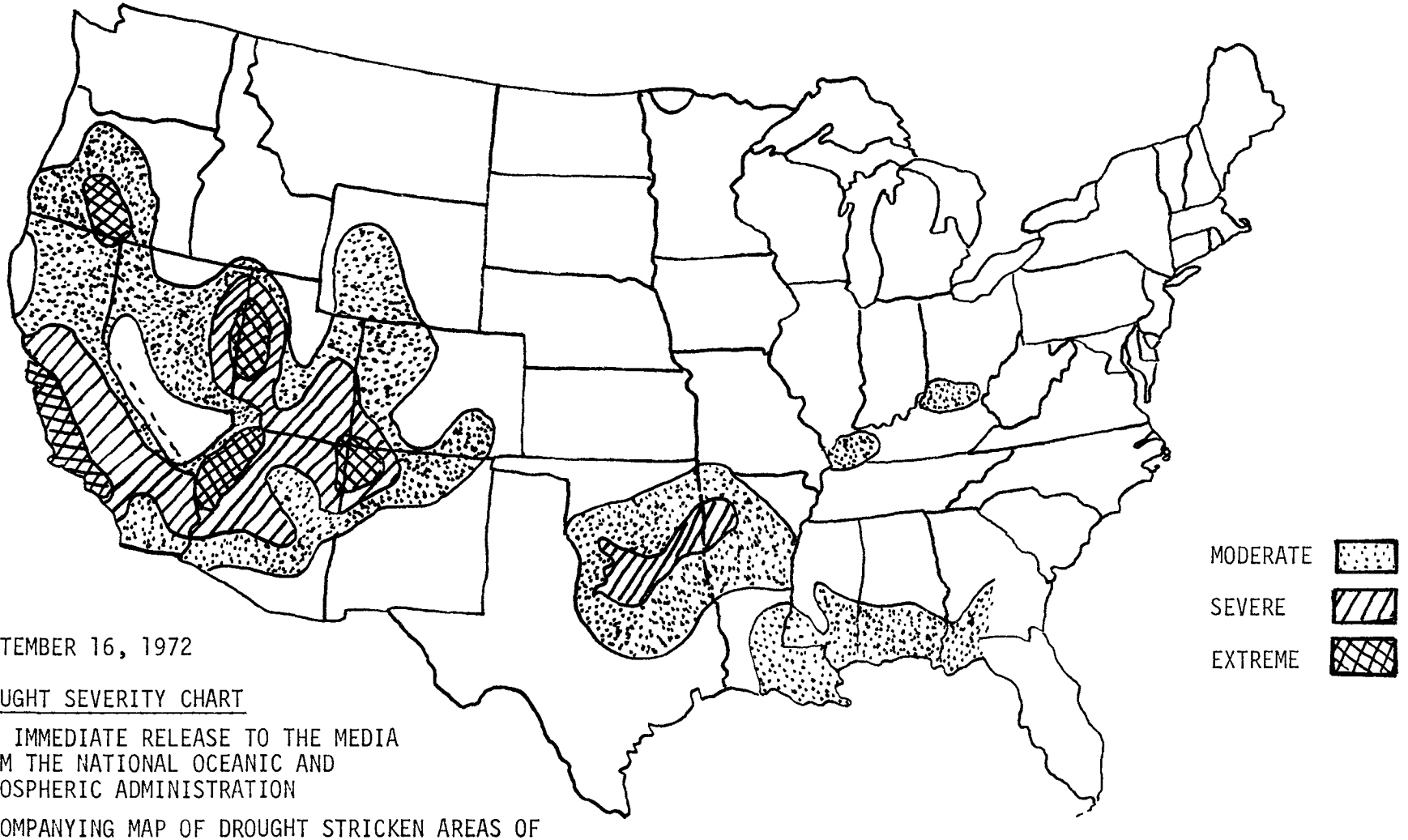
BENEFITS OF CLOUDSEEDING

The benefit to cost ratio is a very important consideration in assessing the value of any cloudseeding project, regardless of whether the user is a farmer, rancher, hydropower company, water engineer for municipal supply, etcetera.

A very logical question for any cost-conscious farmer, rancher, or indeed any user, to ask is: How much benefit in dollars shall I receive for each dollar spent?

Based on our cloudseeding operations in Oklahoma in the 50s, 60s and now reinstated as of April 1972, results show a conservative estimate of rain increase during the crop season of over 30 per cent. This is supported by many of our cloudseeding projects in other parts of the U.S. and in foreign countries. In addition, claims by several other operators tend to substantiate this estimate.

The annual cost of a cloudseeding program in Oklahoma at present is based on an assessment of 5 cents per acre. About one-half of the acreage is



SEPTEMBER 16, 1972

DROUGHT SEVERITY CHART

FOR IMMEDIATE RELEASE TO THE MEDIA
FROM THE NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION

ACCOMPANYING MAP OF DROUGHT STRICKEN AREAS OF US WAS PREPARED BY WAYNE C. PALMER OF NOAA'S ENVIRONMENTAL DATA SERVICE.

Figure 5.

Little rain and above normal temps have accelerated the drying in the south central Gulf states. This area of moderate to severe drought is centered in southern Alabama. The area has been abnormally dry since April of this year. The dry area in the south central Plains had below normal rain and about normal temp. The western drought areas benefitted by some light precipitation and below normal temps.

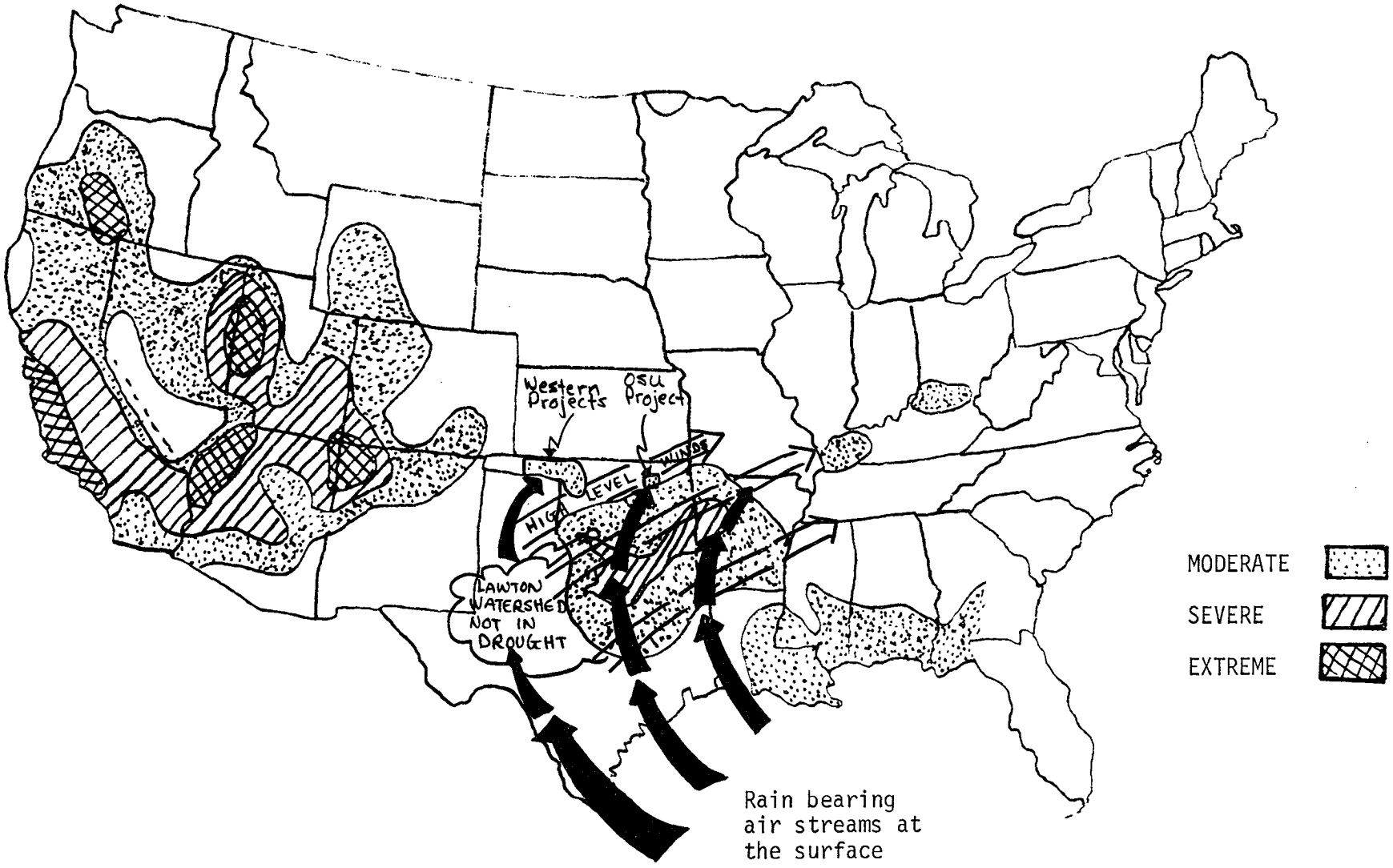

Western Projects
OSU Project
LEVEL
WINDS
HIGH
LAWTON WATERSHED NOT IN DROUGHT
MODERATE
SEVERE
EXTREME
Rain bearing air streams at the surface

Figure 6.

planted. If one uses a conservative rainfall increase of 3 inches during the growing period and assumes this augments yield by only 2 bushels per acre per inch, a benefit to cost ratio of 120 to 1 is achieved. This assumes of course that the price of wheat will remain around $2.00 per bushel. Crops such as cotton yield even higher benefit to cost ratios. Additional rainfall to assure adequate pasturage is also a "must" to increase cattle production during drought.

Currently in Oklahoma the rains in all cloudseeding projects for farm and rangeland have assured those supporting them a substantial return on their investment. Following the first 3 months of operation since August 1972 in Cotton County the users claim that the winter wheat crop is made by virtue of its recent response to rainfall attributed to cloudseeding. The yield from the harvest next June will tell the final story.

Leaders in this area are announcing that the benefits of the weather modification program they are supporting already exceed by a hundred fold the investment in the program. Thus farmers who were disappointed when they sold their wheat early in 1972, before the Russian trade agreements, will not only be compensated for this loss, but added gains will accrue because of additional yields they can expect from cloudseeding together with the higher price of wheat now prevailing.

If it is possible to sustain these results in all cloudseeded areas for a number of years, evaluations will gain in statistical significance. We are satisfied that the effects are real and are based upon physical phenomena because they coincide with results achieved in hundreds of our projects throughout the world over a period in excess of 20 years.

Obviously, then, if approximately normal rainfall can be achieved during the anticipated drought years which lie ahead, evidence will be forthcoming to support the view that regional cloudseeding for environmental management and the stabilization of economic and social values in these areas of recurring drought is valid and of far-reaching importance. This is the objective of the programs now in force. Thus cloudseeding may become an accepted new technology in agriculture, very much as the use of fertilizer and pesticides have achieved such a position.

CONCLUSIONS

It would appear that applications of available knowledge in the fields of long range weather prediction and weather modification will permit advances in environmental management whenever an informed public demands such action. Several representative categories in which these techniques may be employed effectively in addition to that discussed briefly in this review may be mentioned.

(1) Air Pollution

It has been found useful to correlate atmospheric carrying capacity to measurements of air pollution concentrations as a function of the various large-scale weather patterns occurring in the atmosphere. For many parts of the world these weather types have been classified and catalogued from an

historical hemispheric weather map series beginning in 1899. This was first accomplished by the author and his colleagues at the California Institute of Technology as a wartime project in the early 40s. The record has been maintained since World War II by the present organization. Long range forecasts are prepared from predictions of the sequence of weather patterns for long periods into the future. Thus when studies are completed relating variations in air pollution within specific air basins to the weather patterns of the past, it becomes possible to project air pollution as a function of the evolving weather processes. Only after studies of this nature have been completed can one assess changes in air pollution unrelated to the weather -- in other words, the true effectiveness of control measures imposed on stationary or moving sources of pollution.

At present those responsible for air pollution control sometimes tend toward optimism following a long period of windy or stormy weather -- conditions which remove most pollutants from the lower air layer. Sometimes an era of air stagnation will follow, characterized by air pollution alerts precipitating public outcries. Such developments can become a source of embarrassment to those who have spoken out claiming that control measures are becoming effective. In truth no improvement may have been achieved, but there is no way to really be certain until the relationships between weather conditions and air pollution can be properly established. Then this variable can be eliminated and the real variations in air pollution measured.

(2) Cleaning Up the Rivers

In addition to control measures usually imposed to reduce effluents discharged into our rivers, weather modification during unusually low water is effective. Such tests have been implemented successfully. One instance was exemplified by a project in Michigan in 1963. Our client, the Dow Chemical Company, wished to maintain full production during the summer of 1963 at its division in Midland, Michigan, and found the effluents from the plant might exceed legal limits during this normal low water interval. Therefore, cloud-seeding over the river drainage was instituted to increase flows. Not only was this phase of the program successful, but farmers in the area received fringe benefits in the form of high yields for the various crops grown there.

When drought struck central Michigan in 1971 and early 1972, farm groups in several counties, remembering the 1963 cloudseeding results, launched a similar operation. Crops responded favorably in the areas under treatment and the program is expected to be a continuing one.

A regional cloudseeding effort in the Upper Colorado River Basin to add to flows and to reduce salinity has been the subject of many studies and reports by the American Institute of Aerological Research and its affiliated operating companies. Such an effort, currently quite practical, may receive attention because of two factors: The Colorado River flows are running below 40 per cent of normal, while at the same time President Nixon has been assuring the President of Mexico that the U.S. will clean up the waters flowing into that country from the Colorado River.

(3) Clean Power

Normalizing river flows to overcome deficiencies in low rainfall years has long been recognized in the hydropower industry, where cloudseeding has been routine for many years. By maintaining high flows, water management practices are improved and power output stabilized. More important perhaps is the fact that water power is clean power and it can be enhanced by cloudseeding.

In Canada, where much of the total electric power production is hydro (some of it exported to the U.S. under treaty agreements), cloudseeding to increase water resources for power development will undoubtedly take on greater importance as the impending energy crisis mounts. Successful cloudseeding projects have been operated by the author and his associates for Canadian interests for 20 years.

(4) Power Plant Siting

The application of weather knowledge can be important in power plant siting. Areas of frequent air stagnation should be avoided. In the past this has not always been the case. Eventually grid systems which take into account such factors can be established. In this way necessary curtailments during predicted periods of air stagnation in one area can be offset by distant plants within the grid simultaneously situated in a favorable weather regime. Here we are talking about rather broad power grids. In time they may include production units in much of southern Canada and the U.S., a conformation undoubtedly already apparent to the electric power industry.

(5) Forestry

Long range forecasting and weather modification can be applied effectively in the woodlands industry to maintain production at prescribed levels. Trees are no different from other crops; growth rates are slowed during drought and accelerated during wetter eras. Leveling out and normalizing rainfall regimes to stabilize production can be an important management tool and is now within reach.

The implementation of many of the suggestions touched on here lies in the future, of course, because an informed public is necessary before large scale efforts can be funded, in spite of the fact that the technology is already at hand.

- - - - -

REFERENCES

Abbot, Charles G. AN IMPORTANT WEATHER ELEMENT HITHERTO GENERALLY DISREGARDED
Smithsonian Institution, May 27, 1941.

Krick, Irving P. A DYNAMICAL THEORY OF THE ATMOSPHERIC CIRCULATION AND ITS USE IN WEATHER FORECASTING
California Institute of Technology, February 1942.

Elliott, R. D. STUDIES OF PERSISTENT REGULARITIES IN WEATHER PHENOMENA
California Institute of Technology, February 1942.

Meteorology Dept. Caltech. SYNOPTIC WEATHER TYPES OF NORTH AMERICA
California Institute of Technology, December 1943.

Arnold, H. H. GLOBAL MISSION
Harper, 1949, p. 166.

Hansman, Frank T. WAVE-FORM ANALYSES AND SYNTHESES OF HIGHS AND LOWS
American Institute of Aerological Research, April 6, 1953.

Krick, Irving P. UNIVAC PINPOINTS THE WEATHER
Systems, Vol. XXI. No. 2, March-April, 1957.

Malone, Thomas F. SOCIETY POLICY ON ETHICS
Bulletin of the American Meteorological Society
Vol. 41, No. 12, December 1960.

Irving P. Krick Associates, Inc. WEATHER AND STREAMFLOW ESTIMATES FOR SELECTED RIVER BASINS, WATER YEARS 1961-62 THROUGH 1965-66.
Irving P. Krick Associates, Inc., December 1961.

_____ IS ANOTHER DROUGHT ON THE WAY?
The Farmer-Stockman, October 1969.

_____ WE'RE SORRY OUR PREDICTION OF DROUGHT IS PROVING TRUE!
The Farmer-Stockman, April 1971.

Krick, Irving P. A VIABLE METHOD OF LONG RANGE WEATHER PREDICTION
Address at 53rd Annual Meeting of the American Geophysical Union at Washington, D.C., April 19, 1972.

Krick, Irving P. REPORTS ON METEOROLOGICAL ASPECTS OF ARTIFICIAL NUCLEATION IN PHOENIX AREA.
Reports 1 & 2, July 1948 & August 1948.

_____ EVALUATION OF CLOUDSEEDING OPERATIONS IN THE PHOENIX AREA DURING THE SUMMER OF 1948.
Report 10, December 1948.

_____ PRELIMINARY REPORT OF CLOUDSEEDING OPERATIONS, EASTERN WASHINGTON, FOR HORRIGAN FARMS
June, 1950

_____ WEATHER MODIFICATION OPERATIONS MANUAL
Water Resources Development Corporation, 1951 -

_____ INCREASING WATER RESOURCES THROUGH WEATHER MODIFICATION
Address at Annual Meeting of American Water Works Assoc., Kansas City, MO, May 7, 1952; AWWA Journal Vol. 45, No.11, November 1952.

_____ WEATHER MODIFICATION AND ITS VALUE TO AGRICULTURE AND WATER SUPPLY
The Royal Society of Arts, London 1954, Vol. CII p.447-468.

_____ CLOUDSEEDING OPERATIONS REPORT JUNE 6, 1956 TO JUNE 6, 1957
For City of Lawton, Ok, Report 368, August 1957.

_____ THEORY AND PRACTICE OF WEATHER MODIFICATION
Address at Texas A & M, September 8, 1957.

_____ WEATHER FORECASTING AND CONTROL, PAST, PRESENT AND FUTURE
Address at Four-States Irrigation Council, Denver, Co., January 12, 1962.

_____ BIBLIOGRAPHY OF SEVERAL HUNDRED RESEARCH AND OPERATIONAL REPORTS BY AMERICAN INSTITUTE OF AEROLOGICAL RESEARCH AND AFFILIATED OPERATING COMPANIES
Testimony at Hearings before the Committee on Commerce, U.S. Senate, on Bills Relating to Weather Modification, Part 2, Denver, Co., March 31 and April 1, 1966, p. 390-449.

_____ CITY OF LAWTON OPERATION
Report for October 1967 through September 1968.

Krick, Irving P.& Stone, Newton C. COMMERCIAL APPLICATION OF WEATHER MODIFICATION
Paper given at Red Deer, Alberta, Canada, March 1971, covering 13 years of Hail Suppression and Rain Increase Operations in Alberta.

Krick, Irving P. WEATHER MODIFICATION FOR AGRICULTURE AND WATER SUPPLY
A paper presented at the Annual Meeting of the Kansas Association of Wheat Growers at Dodge City, KS, Dec. 1, 1972.

Oklahoma State Bd. of Agriculture OKLAHOMA CROP AND LIVESTOCK REPORTING SERVICE DATA
1967, 1969, 1970, 1971.

_____ WHEAT YIELD DATA FOR 1972 (unpublished)
By letter September 25, 1972.

US. Dept of Commerce, NOAA WEEKLY WEATHER & CROP BULLETIN
U.S. Dept. Agriculture Statistical Reporting Service, May through October 2, 1972.

- - - - -

REPORT ON RAPID CITY FLOOD OF JUNE 9, 1973

Pierre St.-Amand
Ray J. Davis
Robert D. Elliott

Naval Weapons Center
China Lake, California 93555

INTRODUCTION

PURPOSE:

On 09 June 1972, a flood devastated those portions of Rapid City and environs located in the flood plain of Rapid Creek. Flooding also occurred on a number of other creeks in the area. It was hypothecated, by some, that such a flood occurred only once in several hundreds to thousands of years.

Moreover, cloud seeding operations had been conducted on that day in an area near to, but not in, the clouds that produced the rain that caused the flood. This led to allegations that the cloud seeding was responsible for all, or a part, of the flood.

Being desirous of collecting such facts as were available, Governor Richard Kneip of South Dakota, directed the South Dakota Weather Control Commission to conduct an investigation of the flood, the weather conditions, the seeding activity, the public safety aspects and related matter.

Mr. Burton Ode, chairman of the South Dakota Weather Control Commission (WCC) authorized Mr. Merlin C. Williams to assemble an investigatory team for the purpose. Gubernatorial authorization was received on 19 June. The Board of Inquiry began work in Rapid City on 21 June and completed a preliminary report on 27 June. On 28 June 1972, this report was presented to the Third Conference on Weather Modification of the American Meteorological Society at Rapid City.

A slightly elaborated version of the report was published by the WCC in December 1972. Because of continued interest in the affair and the publication by Metzger and others in the popular press of distorted versions of the event, we feel that a wider circulation of the facts, such as we could determine them might be of use to a wider audience. We have therefore prepared a shortened version for publication in this journal. Only those details pretinent to the matter are included here. If the full report is required, one should be requested from the WCC.

PROCEDURE

We obtained such facts and data as were necessary to the inquiry by interviewing persons involved in the meteorological, hydrological, public safety and weather modification aspects of the flood. In addition, we compiled and reviewed such correspondence, newspaper articles and similar material as we could. A search of available flood records was made.

RAINFALL AND FLOOD DATA

Data made available by the Rapid City Engineer's office indicates the extent of the flooding and provides evidence that the peak flow was perhaps in excess of 13,000 cubic feet per second and perhaps as high as 50,000 cfs. Figures 1a and 1b are abridged versions of maps prepared by his office showing the area flooded. The details of death and destruction caused by the flood are reported in the press, and are being tabulated by others. We will not discuss these in detail.

Figure 2 shows the distribution of rainfall prepared by Mr. Larry Longsdorf of NOAA, Kansas City, on the basis of a bucket survey. Rain fell over most of the Black Hills and part of the flat lands, but the greatest part of the water fell along a northerly trending line from Keystone to Sturgis.

- - - - -

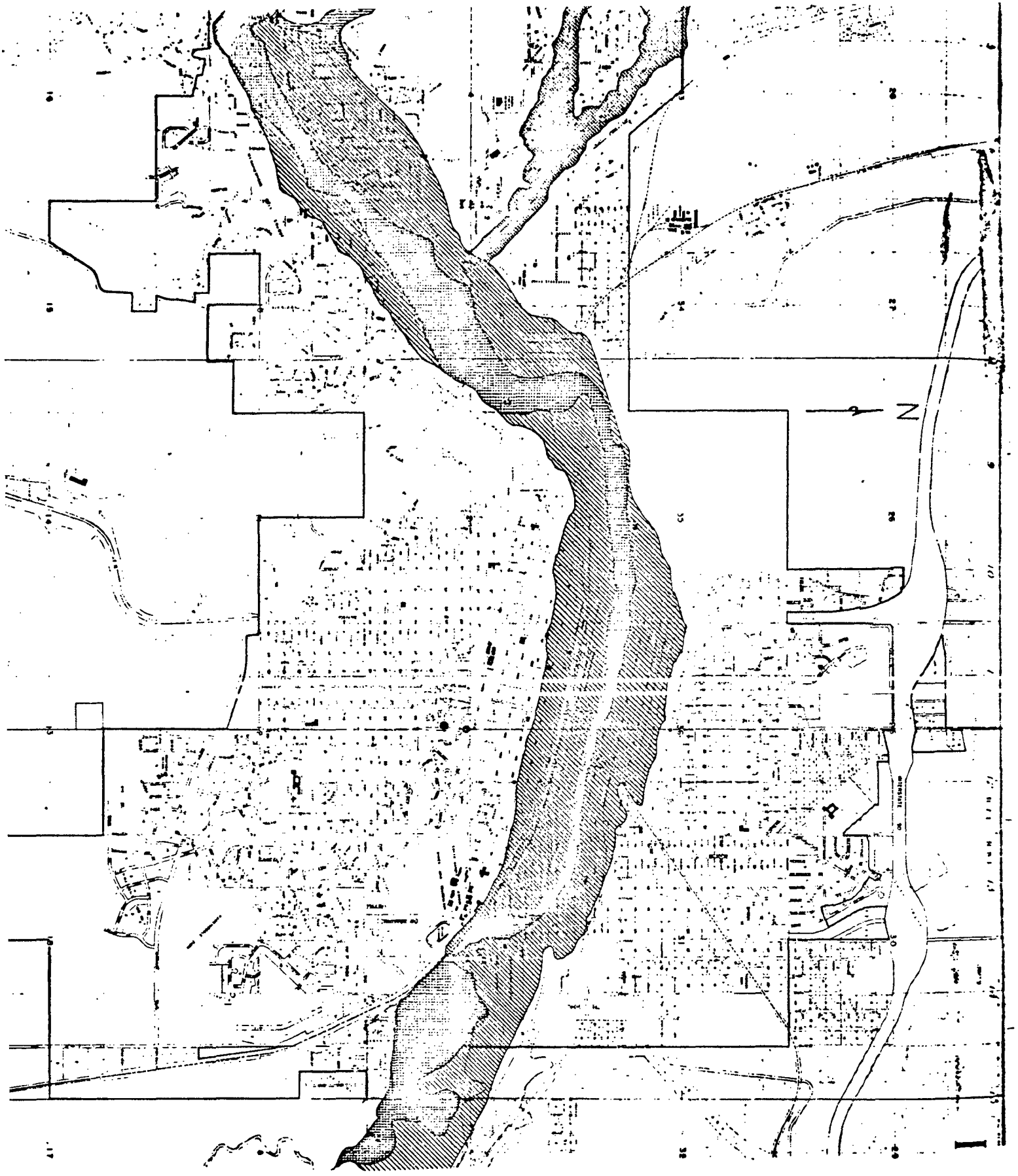


Fig. 1a Historical flood area map. The area flooded in 1907 is indicated by slanting single hatching; in 1949 by vertical single hatching; 1920, 1927, and 1952 by vertical and horizontal hatching; and 1962 by double slanted hatching.

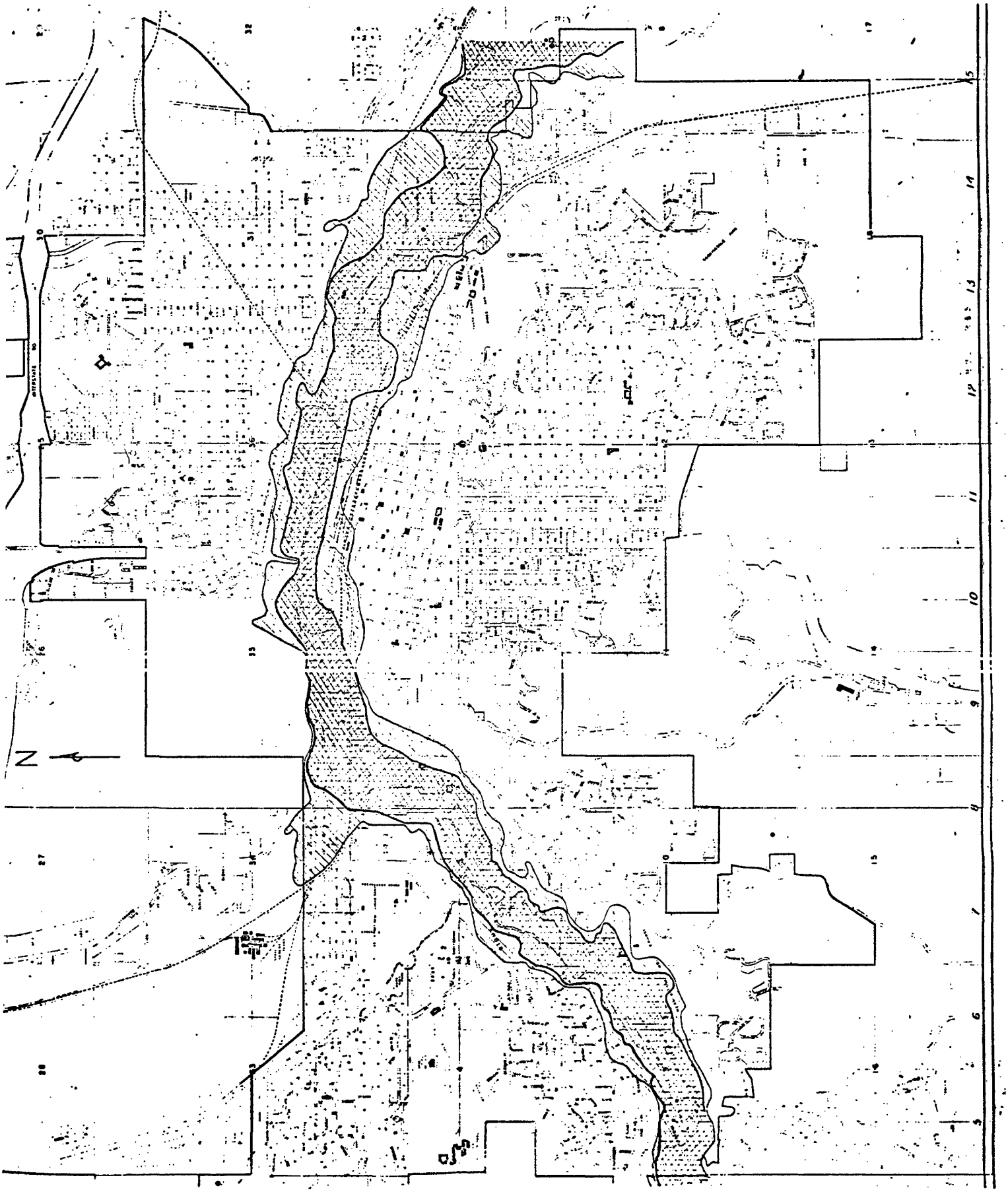


Fig. 1b 1972 flood map. The heavy solid line encloses the area of flooding.

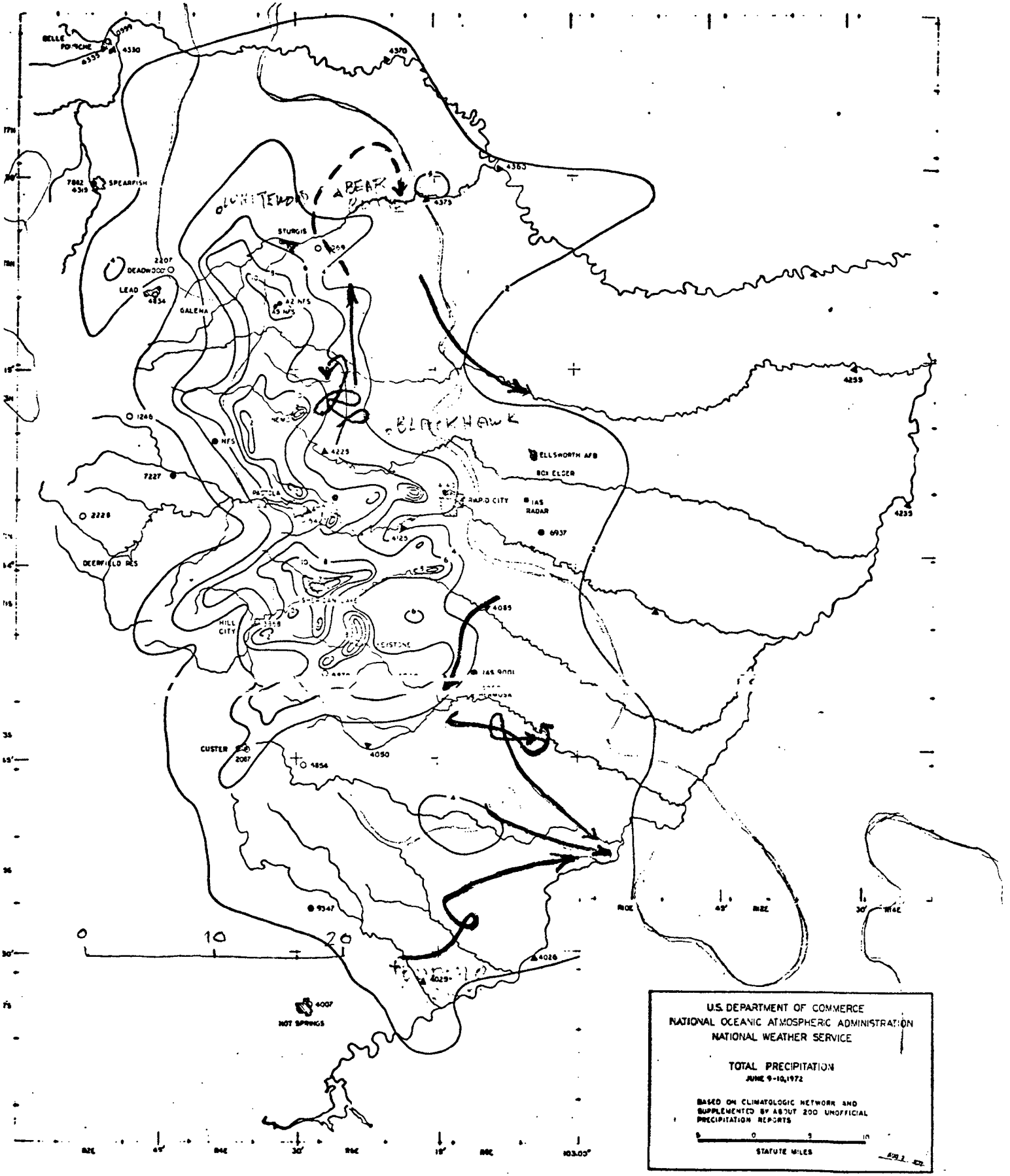


Fig. 2 Map of storm rainfall distribution based upon bucket survey by Mr. Larry Longsdorf of NOAA, Kansas City.

I. WEATHER PATTERN

WEATHER EVENTS

The weather pattern at the time of the flood producing rains consisted of a strong east to southeast wind, on the eastern flank of the Black Hills, from the surface up to 30,000 feet, with a variable or light westerly flow above. To the west of the Black Hills a westerly flow of perhaps 15-20 knots persisted to high altitudes.

A description of the situation as it appears from the west was furnished by Col. O. D. Filley, USAF Ret. He passed through Sheridan, Wyoming between 1430 and 1500. He estimated the surface wind there at 12 to 15 knots out of the west. He arrived in Spearfish at 1830 in heavy rain, having noted a 15 knot westerly surface wind all the way. He noted a line of monstrous cumulonimbus clouds visible from 60 to 75 miles east of the Black Hills. Anvils were blowing to the east. This indicated developments prior to 1630 with visible tops around 40,000 feet. The clouds look from the west just like local Plains storms.

At Spearfish, however, the wind was calm. He reached Trout Haven, 20 miles south of Lead-Deadwood at 1900 with heavy rain continuing. He assumed that by 1915 the high water had already passed the junction of Highways 20-385. He reached Black Forest Inn at 1930, still very heavy rain and much lightning but with no surface wind.

The southeast flow, on the east side, was especially strong at about 10,000 feet where the evening sounding at Rapid City showed a 40 knot wind. This flow fed moisture-laden, warm air into the complex of cumulonimbus clouds over the eastern face of the Black Hills, where the convective activity raised the moist air through updraft cores to as high as 45,000 feet. Largely because of the triggering of new convection on the east side, within the moist airflow, and the lack of a strong westerly flow at higher levels, the main cloud mass remained essentially stationary. This, rather than the large size of the storm itself, accounts for the extraordinary rainfall on June 9th.

The antecedent weather patterns during the 8th and early 9th of June involved the movement of a short-wave, upper air trough line from the west coast to the western fringe of the Great Plains. This trough line was oriented generally north-northwest to south-southeast and moved toward the east-northeast. Figure 3 contains maps illustrating the movement of the trough line across the western part of the country from 1600 MDT on the 7th through 1800 MDT on the 9th. Just ahead, to the east of the trough lay a 250 mile wide tongue of moist air. This moist air tongue was produced by movement of water-laden warm air from south to north in strong southerly flow ahead of the trough. This air was brought to the condensation level by the upward motion in this tongue, resulting in the production of clouds and rainfall. The upward motion itself was produced by a combination of convection and synoptic scale low level convergence ahead of the trough. Strong thunderstorm activity and flash floods were reported as this trough, and the moist band, moved eastward from California through the Great Basin

and into the Rockies during the 8th and the early part of the 9th of June. The sequence of warnings and comments in the National Weather Summary associated with the different maps appear on theright hand side of Figure 3.

On moving east of the Rockies during June 9th, the trough moved aloft over a surface cold front that extended from just east of the mountains in Montana through northeastern Wyoming and into extreme southwestern South Dakota.

In the shallow layer of slightly cooler air lying to the north of this cold front the wind was easterly, driving this colder air up over the Black Hills and thus adding orographic lift to the net upward component of motion of the moist air lying at higher levels.

An interesting and relevant aspect of the synoptic scale (broad) weather pattern was the presence of a tongue of dry air several hundred miles wide, lying between 15,000 and 30,000 feet, just ahead of the moist pre-trough tongue. It is impossible to account for this, except as the result of subsidence of air from higher levels resulting in warming and drying of the air. This was probably the downward branch of a meridional circulation pattern (normal to the trough line in the vertical plane), of which the upward moving was in the wet tongue.

The morning National Weather Service (NWS) rawinsonde (0600 MDT) on the 9th at Rapid City was taken when this dry tongue lay over the region, Figure 4. The next NWS sounding was taken 12 hours later at 1800 MDT right in the moist tongue, Figure 5. When the morning sounding was put into the Institute of Atmospheric Sciences' (IAS) convection model, the prediction was for development of moderate cumulus clouds with peak updrafts of about 20 meters per second. When the evening sounding was put into the model, a very different prediction was produced. Severe cumulus development was indicated with peak updrafts of 47 meters per second.

Although the synoptic scale disturbance, consisting of the trough, the moist tongue and the dry tongue, moved consistently at the rate of about 360 nautical miles per day across the western part of the country, it must be emphasized that the individual convection cells developing within this system did not necessarily move with the same speed. In particular, the main convenctive cloud mass over the Black Hills during the evening of the 9th was stationary, as shown by radar information from Ellsworth AFB. The low level easterly flow against the Black Hills induced by the low level cold front, as described above, played some role in this situation. The arrival of the moist tongue at the time of day most favorable for triggering of convective activity over mountainous terrain also contributed to the development of a stationary system.

Although the air mass over the region during the morning of the 9th was quite dry from 15,000 to 30,000 feet, there was fog on the ground at the airport in the early morning hours. The NWS station reported this as lifting to a low cloud deck that remained during the forenoon, tending to break up at midday. By 1555 MDT towering cumulus were reported in all

quadrants. The Institute of Atmospheric Sciences had been observing, on their radar, maximum tops in the 40,000 to 50,000 foot range about this time. The NWS continued to report lightning and thundershowers, generally south through west to north, all during the remainder of the afternoon and evening. At Ellsworth AFB the radar detected echo tops at 23,000 to 43,000 feet during the evening of the 9th and the early morning hours of the 10th. There were large areas of cells having diameters of five to ten miles. At 1930 MDT the main radar echo stretched out north-south along the eastern face of the Black Hills as indicated by the Ellsworth AFB radar. Figure 6 shows the horizontal and vertical distribution of radar echoes in the Ellsworth radar scope. The pictures were kindly given us by Major R. F. Strand, Commander, Air Weather Service Detachment, Ellsworth AFB, through the courtesy of the base commander, Col. Barnett. The range-height indicator (RHI) showed echo tops around 40,000 feet.

The NWS reported generally easterly surface wind during the 9th with speed around 20 knots with gusts to 30 knots in the afternoon and evening. Two minor aircraft landing accidents occurred. Visibilities were reported to be about 10 miles due to haze. Aloft, the IAS plane reported haze restricted visibilities of under one mile. In spite of the haze, Major Strand was able to observe an anvil cloud containing mammatus formation directly overhead between 1800 and 1900 MDT. Around 1800 MDT, IAS personnel noted an intense radar cell covering the general area of Keystone and Pactola.

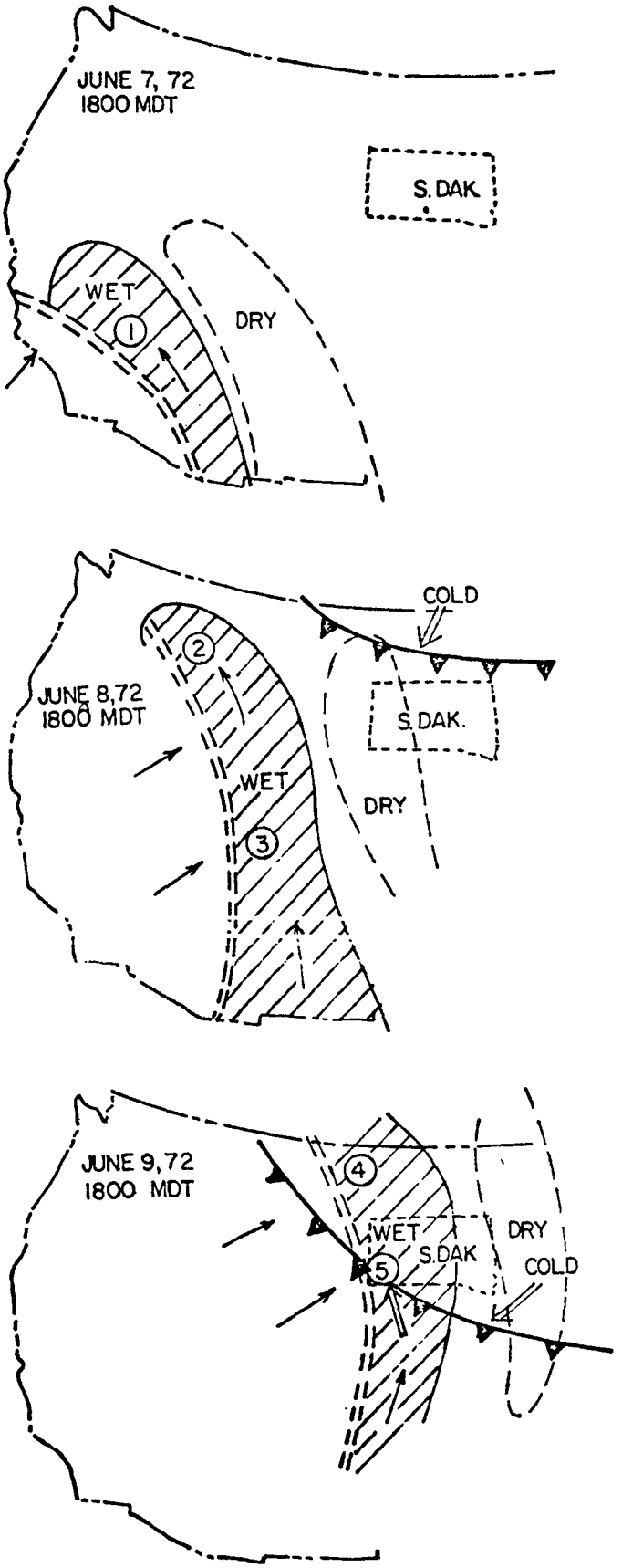
It appears that heavy rain had been in progress in the area of flooding prior to 1800 MDT. A recording type gage record from near Nemo, about 15 miles west-northwest of Rapid City, indicated heavy rain commenced about 1700 MDT. The sheriff of Lawrence County received a call around 1800 MDT stating that Boulder Creek was flooding. The call was investigated, and flooding was found to exist along with a heavy downpour. State Radio was informed of this by the sheriff. By 1845 MDT word was passed via state radio to the National Guard. At 2030 MDT peak flooding occurred at the junction of Highways 40 and 385 on Deer Creek which is a tributary to Rapid Creek, and at about 2300 MDT the peak had arrived at Canyon Lake Dam.

The NWS issued its first flood warning at 1915 MDT for the northern hills; this was received by Civil Defense, State Highway, local police and radio stations at Rapid City, Deadwood, Belle Fourche and Sturgis. By 1945 to 2000 MDT the National Guard was activated and by 2000 MDT evacuation of the Dark Canyon area was commenced. At 2000 MDT the NWS issued its second warning specifically pinpointing the Rapid City and Box Elder flood hazard.

At around 2030 MDT Mr. Alex Kocielski phoned to Prof. Arnett Dennis, both in Rapid City at the time, that he had observed a tremendous cloud to the west having almost steady lightning discharges and that he estimated on the basis of low level cloud motion that the velocity of inflow was 50 mph.

INFERENCES CONCERNING CLOUD MORPHOLOGY

From the foregoing outline of weather events and descriptions of air motions and of radar observations, certain inferences can be drawn concern-



EXTRACTS FROM THE
NATIONAL WEATHER SUMMARY

1

6-7-72 2:52PM CDT - The drought stricken SW is pocked with sporadic showers & thundershowers, and flash flood warnings are in effect for the interior & desert regions of southern Calif. as locally heavy thundershowers occur in the mountain and deserts.

2 & 3

6-8-72 9:17PM CDT - A severe thunderstorm watch has been issued for portions of central & NW Washington & a small portion of north central Oregon until 11PM PDT.
Locally heavy showers with possible flash flooding are expected in Utah tonight and heavy showers may also occur in eastern Montana tonight. South central Texas expects some locally heavy rains tonight and Friday.
A flash flood watch remains in effect for western Colorado west of the continental divide early tonight & again Friday afternoon & early nighttime hours. Heavy hail was reported 7 miles west of Alamosa, Colorado late this afternoon from a thunderstorm.

4

6-9-72 9:17PM CDT - A funnel cloud was sighted by the public about 3 miles south southwest of Billings, Montana in the midafternoon.

5

6-10-72 2:52PM CDT - Heavy activity produced torrential rainfall late Friday to early this morning down the east slopes of the Black Hills of SD. As much as 7 inches of rainfall was reported. The high water swept through Rapid City taking a toll of death & destruction. The latest count as of 10AM MDT from the Corps of Engineers indicated 55 dead and 300 missing.

Fig. 3 Schematic depiction of upper air weather features for 1800 MDT on the 7th, 8th and 9th of June. The trough line is marked by double dashed lines, the tongue by a single solid line, and the dry tongue by a single dashed line. Arrows indicate the 10,000 foot airflow. The numerals on the maps refer to the text on the right hand side.

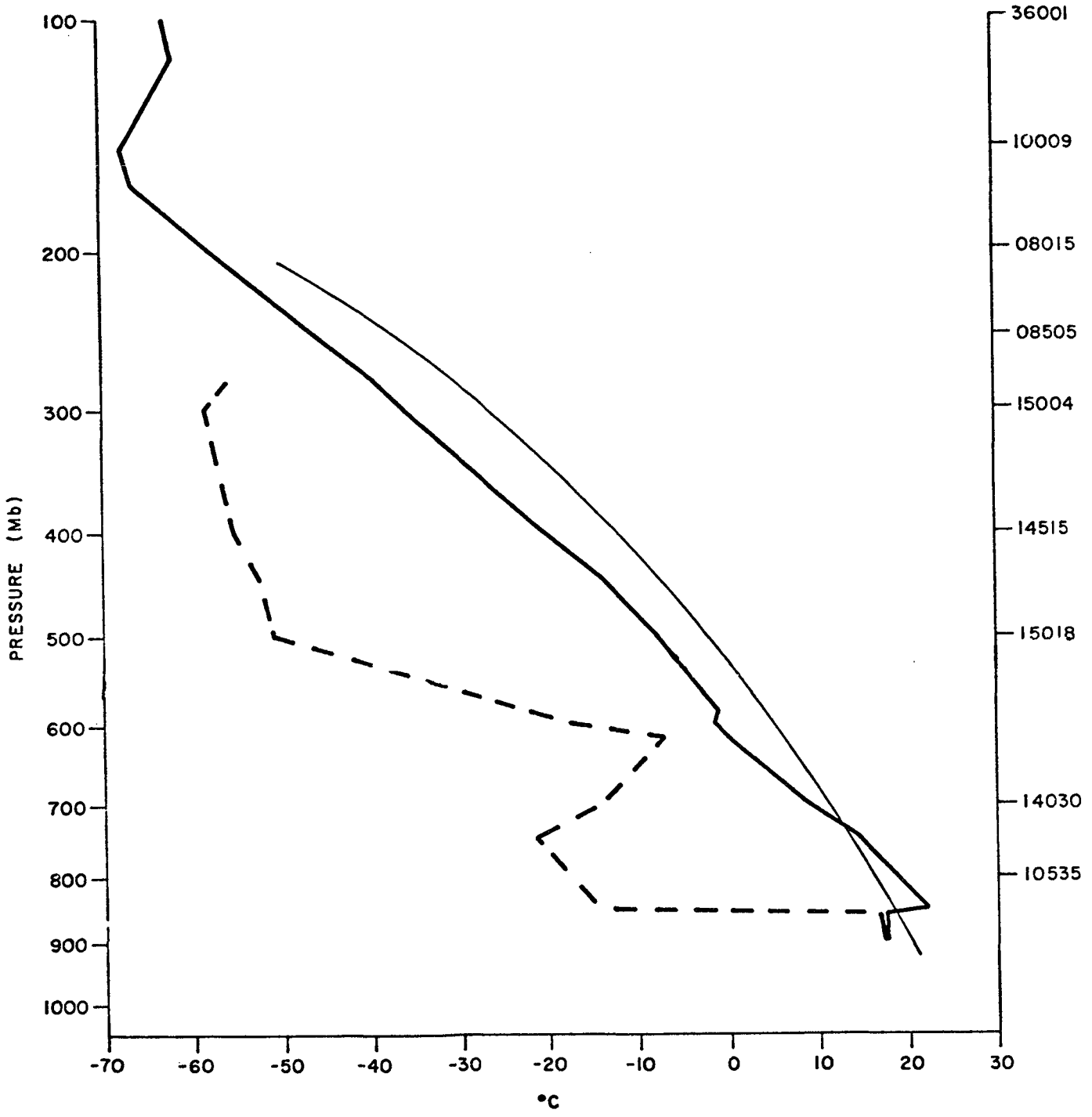


Fig. 4 Sounding for 12Z (0600 MDT), 9 June 1972

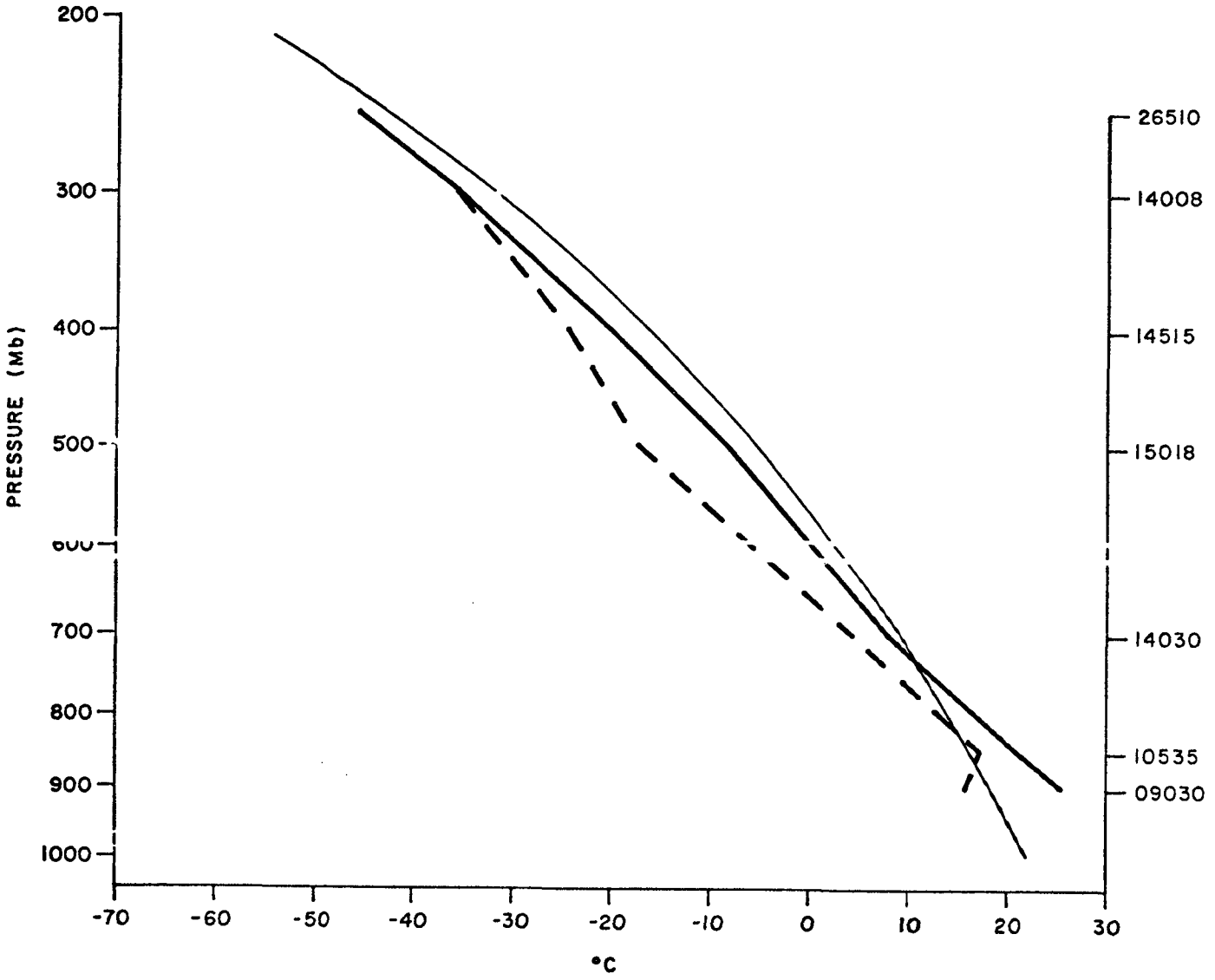


Fig. 5 Sounding for 00Z (1800 MDT), 10 June 1972

ing the structure of the cloud system over the Black Hills responsible for the flood producing rains. The system was a stationary zone some 80 miles long and 12 miles wide, lying in a north-northwest, south-southeast orientation along the eastern face of the Black Hills. Embedded within this massive cloud system were indifidual cumulus cells of 5-10 miles diameter showing very little horizontal motion and having tops in the 40,000 to 45,000 foot range with a few in excess of 50,000 feet. The system produced heavy rainfall from several hours before 1800 to early morning. Total rainfall amounts, as shown by the flash flood rainfall map (Figure 2), covering the area crucial to Rapid City, based upon a bucket survey, ranged from four inches around the periphery of the system to peaks of 12-14 inches along its midline.

The generalized outline of the cloud boundaries and the airflow (averaging over the transient updrafts) is shown in Figure 7, a vertical section through the cloud oriented west to east. The figure shows a strong flow from the east toward the hills below 15,000 feet which was deflected upward above the hills, and then was deflected again and flowed eastward at levels above 25,000 feet as an anvil cloud. A weak, westerly low level wind flowed into the cloud system on its western flank as indicated by the arrows there. Growing "feeder" cumulus clouds moved westward into the system as shown on the right side of this diagram. Similar but probably smaller "feeders" developed on the west.

This is a reverse shear situation, with the airflow pattern remaining stationary. The precipitation was initiated by the warm cloud, droplet coalescence mechanism. On rising above the freezing level (about 14,000 feet) some hydrometeors were frozen and diffusional growth of ice crystals became important as did accretional growth at higher levels. When the hydrometeor particles were of sufficient size to fall out, most fell through cloud forms between active updrafts. Some drops rose into the anvil and then fell into the feeder clouds lying just east of the main cloud system and were reprocessed. Such a system is highly efficient because little cloud water condensed in the updrafts is evaporated and lost for precipitation in either the anvil or in the subcloud layer which is ingesting saturated air from the east. This type of system can maintain a steady state until the diurnal cooling in the early morning hours commences to quench its activity.

The system was not extraordinary in size or vigor for this area; its flood-producing nature was the result of its remaining stationary for so long.

The usual Great Plains thunderstorms develop in what is called a positive shear situation. These clouds move with the wind and, although rain rates are quite high, frequently two inches per hour, they distribute their rainfall en passant, usually wetting down a given point for only an hour or two at the most. The reverse shear type usually moves more slowly, occasionally upwind or laterally, and frequently is stationary. The aggregate rainfall from these at any one point is therefore more than received from the usual air mass cloud over the Great Plains.

The occurrence of these clouds in the Rapid City area is not common. They have been observed in the past, but experience in seeding them is lacking. Peripheral clouds are frequently advected into the main mass, especially on the side from which the low level flow is advancing.

They recycle a significant portion of previously processed air. Humid air, laden with drops, falls from the overhanging upper edge and is ingested and processed again in the growth of these clouds. The growth and duration of these clouds are thus not limited by the available lower level moisture, and they are very efficient rain producers. Rainfall amounts of at least 14 inches were estimated to have fallen on June 9th. No estimates of maximum rainfall rates are available, but estimates in excess of two inches an hour were common. One observer reported four inches in 30 minutes.

The important factor here was that the cloud remained stationary over the Black Hills for several hours so that the aggregate rainfall reached Draconian proportions.

II. CLOUD SEEDING

WEATHER MODIFICATION ACTIVITIES IN SOUTH DAKOTA

Two important weather modification programs are being conducted in South Dakota. One is a statewide program operated by the state under the direction of the South Dakota Weather Control Commission and financed by state and county funds. The main goal is to augment rainfall during the summer months. A secondary goal, pursued on special occasions, is reduction of hail.

Seeding for rainfall augmentation is done by using silver iodide produced by acetone burners mounted on aircraft. On some occasions pyrotechnics are used to supplement the acetone burners. The seeding operations are conducted following coordination with county officials who determine if more rain is wanted and where.

In the Black Hills area, the Institute of Atmospheric Sciences, of the South Dakota School of Mines and Technology, received state support for certain research activities in connection with the statewide program. Between May 1 and June 5 the state provided one aircraft and seeding materials for use over Lawrence, Custer and Pennington Counties. The counties provided funds to the IAS for direction of the seeding and observation of the results. The work was done during daylight hours only. No federal agency participated.

On June 5, in accordance with the three-way contract terms between county officials, IAS and the WCC, the state-supported seeding was stopped and the equipment was withdrawn from the Rapid City area and moved to Perkins and Harding County to be operated out of Bowman, North Dakota, under the control of Wilbur Brewer, to avoid interference with research activities being conducted in the area by IAS under a Bureau of Reclamation sponsored research program known as "Cloud Catcher".

In addition, Lawrence, Pennington and Custer Counties provided funds to the IAS for an operational, airborne, silver iodide seeding effort to be conducted on weekends and holidays during the period June 5 to August 15. WCC participation during this period was to consist of providing acetone-

silver iodide materials for operational periods. This effort was supervised by Dr. R. Schleusener in accordance with policy recommendations by an Advisory Board composed of the Director, WCC, Dr. Schleusener and one official from each county. The work was suspended on June 10 and on June 19 the three counties authorized resumption of the weekend program in certain areas where water was needed.

Project Cloud Catcher was to be conducted from June 5 to August 15. It was to be conducted during daylight hours, five days a week, exclusive of weekends and holidays. The program consisted of a three-way randomized study that divided its efforts between seeding with common table salt, with silver iodide, and with nothing. The experiment was further stratified into seeding updrafts below particular cells and the seeding of areas without regard to the presence or absence of clouds.

At a morning briefing, based upon forecasts and computer analysis, a decision is made as to whether to conduct an experiment on that day, and if so, the type of agent to be used. For the rest of the day, operations continue in an almost automatic manner. Only the pilot of the seeding aircraft, operating under sealed orders prepared at the beginning of the season, knows if seeding is actually being conducted. The field director remains at a radar site, located east of Rapid City. He knows on a given day which seeding agent might be used and that one-third of the time he is not seeding at all. He has the option of choosing to conduct the exercise on individual clouds or over areas.

To the best of our knowledge, no other persons were operating seeding projects or dispensing seeding agents in the Black Hills area. Ground based silver iodide generators had been removed from the field and were in storage. Dr. Jack Reddin, Geologist, informed us that no active smelters exist in the Black Hills and hence no potential ice forming nuclei from this type of source were being emitted. The cement factory in Rapid City has electrostatic precipitators and was not emitting any consequential amounts of dust or ash.

One possible source of hygroscopic nuclei in the Black Hills and vicinity is sawdust burners. Several are located in the Black Hills and approximately ten more in the affected area. No estimates of the amounts of effluent are available.

CLOUD SEEDING ON JUNE 9, 1972

The National Weather Service prepared a meteorological sounding at 1200Z, 0600 MDT; this was received by the IAS and incorporated into an analysis of the local weather pattern.

At the time, the validity of the 1200Z sounding was questioned by Mr. Alex Koscielski, Research Meteorologist at the IAS and Director of Project Cloud Catcher. As it developed, the personnel at the NWS station, and indeed everyone else who saw the soundings, thought it aberrant. A very moist layer at the ground was overlain by an extremely dry layer, so

dry as to cause question as to the correct functioning of the instrument. However, further investigation has disclosed no evidence that the instrument malfunctioned, and, as explained in the section on meteorology, the dry layer did exist. This point is crucial to an understanding of what followed.

The analysis prepared by the IAS took account of a front near Chadron, Nebraska and of an area of high easterly winds to the north of the Black Hills. Information used in the morning analysis by the IAS did not indicate to them, at that time, that severe weather over and above the usual cumulus activity was to be expected. As a part of the analysis, certain calculations were made by means of a computer. The morning sounding was used, and it appears that some cumulus activity was possible. Then, because the sounding was in question, the computations were made with several modifications to the morning sounding, so that twice the observed precipitable water was considered. This gave rise to a solution that indicated that considerable, but not catastrophic, cumulus activity was possible. Finally, it was decided to consider the original sounding in the analysis. It was decided to continue with the day's activities and sodium chloride was selected as the seeding agent.

Once the decision to proceed had been made, the crew took their stations and began work. No further soundings were made locally until the NWS sounding at 0000Z which was not available until about 1945 MDT, some two hours after the last seeding was completed.

An afternoon analysis by IAS indicated increasing cloudiness and possibility of strong easterly winds, but foretold nother alarming. The details of this analysis were not available at the time of seeding, nor was the NWS 0000Z sounding. An after-the-fact appraisal of this sounding leads to the conclusion that very strong convective instability was present on or before 1700 MDT.

Two seeding flights were conducted on June 9th. At about 1430 MDT the seeding aircraft was launched with 350 pounds of salt. The salt used was known as Mortons 200 Fine and consisted of sodium chloride ground to a size range of 3 to 200 microns with a mean diameter of 35 to 40 microns. The salt contained a minor amount of a free flowing-agent, probably tricalcium phosphate.

The aircraft was directed to some radar echoes in the vicinity of Sturgis, Figure 8. At 1505 MDT, 100 pounds were dispensed in updrafts beneath the clouds. Another 100 pounds were dispensed in an area seed mode. At 1524 MDT, the radar contact was lost due to precipitation echoes and to the low altitude at which the aircraft operated. In order to avoid an area of intense rainfall the pilot deviated to the north and west, flew around Bear Butte and eastward over the plains east of the Black Hills. During this time he estimated that about 50 pounds were dispensed owing to extreme turbulence. The aircraft was reacquired by the radar and between 1537 MDT and 1543 MDT the remainder of the salt was dispersed in an area seed mode, about 100 pounds. Operations were conducted at an elevation of 1500 feet above the terrain. The pilot reported a widespread dense haze that reduced visibility in the vicinity of the hills.

The aircraft returned to Rapid City, reloaded and took off again. Prior to this second launch of the seeding aircraft, Mr. Koscielski and Dr. Dennis discussed the advisability of undertaking the second test case because of the chance of local flooding in the hills (see Appendix A). By this time the wind had freshened to around 30 knots from the east. Initially, it was thought that the aircraft would work over the hills to the west of Rapid City. Flying conditions were so poor that the project director elected, on grounds of aircraft safety, not to do so and instead the aircraft was directed to an area midway between Rapid City and Hermose to Buffalo Gap. The seeding tracks and amounts are shown in Figure 9. The seeding began at 1639 MDT and continued intermittently until 1737 MDT.

Cloud bases in the area seeded were 2,000 to 2,500 feet above terrain. Visibility was at times 3/4 mile in haze and less in rain. Turbulence was moderate to severe. The pilot, a very experienced man, had difficulty controlling the aircraft. Updrafts at cloud base of 1500 feet per minute were noted. Updrafts of 300 feet per minute, sustained for three minutes of flight, i.e., eight to ten miles along the flight track, were common. The rate at which salt was dispensed varied somewhat because of the turbulence.

Between 1715 MDT and 1730 MDT, Mr. Koscielski called the NWS and advised of the possibility of flooding in the Sturgis area. At 1815 Dr. Dennis, who was at the radar site from 1450 MDT to 1830 MDT, called NWS to warn of heavy clouds and possible flooding over the hills to the east of Rapid City. The main radar was shut down at 1810 MDT and all IAS radar at 1900 MDT.

During the day lower clouds obscured the development of cumulus over the Black Hills, and only through occasional breaks in the clouds could the size of the developing cumuli be appreciated. Mr. Koscielski informed us that at about 1430 MDT the cumulus towers showing a reverse shear were forming. Air Weather Service personnel at Ellsworth Air Force Base noted this effect in the late afternoon and were able to give excellent descriptions of the clouds.

The Ellsworth weather radar was inoperable for part of the day, but was used in late afternoon. The repeater scope at the NWS station was not available and some difficulty with the relay system prevented its use during the evening. The AWS personnel did, however, call in to NWS information that the cloud was stationary, of massive proportions, likely to yield heavy rain, and that flooding was possible.

- - - - -

III. EFFECTS OF CLOUD SEEDING

Two methods of cloud modification are in common use. The most widely employed technique is that of seeding with glacogenic agents. The other is to use hygroscopic agents. Because the two techniques effect clouds quite differently, we reviewed these methods and the basic differences in some detail on page 20 through 23 of the original report. We will not repeat this material here because the WMA members already understand this matter.

EFFECTS OF SEEDING ON JUNE 9

The details of the seeding of June 9 have been presented earlier in this report. It appears that because of poor visibility and lack of appreciation of the unusual nature of the cloud forming over the Black Hills that feeder cells associated with the main storm may have been seeded by the addition of salt. The cells seeded during the first sortee probably moved northwestward and joined the main cloud mass to the north of the hills and over the plains. The clouds seeded on the second sortee marched into the main cloud mass. Some perhaps collapsed before being incorporated into the bulk of the storm and some may have persisted. This point cannot be demonstrated with assurance. It can be asserted with confidence that they were, however, outlying memebers of the main system.

In view of the uncertain knowledge of the effects and processes involved, it cannot be demonstrated that the rainfall in the main cloud was altered by the seeding activities. There is no showing that this particular instance of salt seeding was a factual cause of the excessive rainfall. We will, however, try to place the situation in perspective by a few elementary calculations.

Individual cells were treated with approximately 100 pounds each of salt. The salt was originally of perhaps 35-40 microns diameter; however, in the presence of moist air it tends to clump and aggregate into large masses, thus reducing the number of particles dispensed. Let us assume, putting it in the most unfavorable light, that the particle diameter was 50 microns and that the entire 300 pounds was placed in one cloud 4 kms in diameter and 15 kms high, containing a concentration of 200 drops per cubic centimeter. Thus, the cloud contains at least 5×10^{19} drops. The total dosage of 300 pounds of salt in the form of 50 micron diameter particles consists of about 10^{12} particles and it appears therefore that the cloud seeders would have added 2×10^{-6} or 0.0002% of the total number of drops in the cloud.

The salt involved may have condensed about eight to ten times its own weight in water before the droplets asymptotically approached vapor equilibrium. Thus, we can expect that the 300 pounds,or 136 kilograms, of salt resulted in the direct condensation of perhaps 1,360 kilograms of water, some of it obtained from evaporation and recondensation of smaller drops with no net energy release. It has been estimated that a large Great Plains thunderstorm processes over 50,000,000 metric tons of water in its

life cycle. Thus, again to state the maximum hypothesis, the cloud seeders condensed 1.4 metric tons of water in feeder clouds that condensed upon their own initiative 50 million metric tons. Thus, from this viewpoint the energy release produced by the seeding was totally insignificant in view of the energy by condensation in large thunderstorms.

Estimates as high as 8×10^5 acre feet of water, or about 10^9 metric tons of water, have been made for the rainfall from the total storm of June 9. These estimates are probably conservative. If all the water condensed by the cloud seeder fell as rain, and it probably did not, then their condensational efforts resulted in only one billionth of the recorded rainfall.

The foregoing does not of course include factors involving a Langmuir-type shower mechanism caused by break-up of droplets and subsequent coalescence. The Langmuir chain reaction is a necessary component of any model capable of indicating that salt seeding will yield economically signigicant extra rainfall. However, an upper bound is set on total rainfall possible from a given cloud and updraft system and this is reached when 100% of the cloud water condensed by the system is removed as precipitation, i.e., when none is lost to evaporation. It has been the hopes of those attempting to develop salt seeding that by early conversion (at low cloud levels) of cloud water to rain drops, the great loss of cloud water by the evaporation of extensive anvils at the top of the cloud could be avoided or reduced.

In the June 9 cloud, such a mechanism would have had no effect, assuming the seeded feeder cloud had merged while under the effects of the seeding with the main cloud, for two reasons. First, there was an abundance of natural condensation nuclei as evidenced by the presence of dense haze, as reported by both ground and aerial observers. The natural cloud physics processes were adequate for the task in this case. The second, and dominant reason, is that a reverse shear type cloud is highly efficient in transforming its cloud water to precipitation. The cloud physics mechanism responsible for this high efficiency in the June 9 case was the ice nucleation process. Supercooled cloud droplets were converted to ice crystals on the natural ice forming nuclei abundant at the high cold upper region of this cloud. These grew to sufficient size to fall as precipitation. Furthermore, the smaller precipitation particles and remaining ice crystals which did not fall to the ground over the Black Hills, were carried into the anvil forward (eastward) of the hills, falling into feeder clouds there. They were thus ingested again into the main system, serving as kernels for further growth. At this time, such a calculation cannot be made realistically. However, considering that the reverse shear clouds are remarkably efficient rain producers, even to the extent of reprocessing their own drops, the cloud probably would have rained as much as it did in any case.

It is inescapable that such clouds have in the past formed and rained without human intervention, and the the meteorological conditions were indeed such that a natural catastrophic rainfall on June 9 was inevitable.

PROPRIETY OF THE SEEDING

While it cannot be shown that the seeding activities of June 9 augmented or diminished the storm and our reasoned conclusion is that the storm was not affected in a way that could have resulted in greater severity, we will comment on the practices employed.

Once the experimental design for the day had been chosen and work had begun, it was continued in the presence of rapidly deteriorating weather. The morning sounding upon which the experiment was based, and the morning analysis were the only formal pieces of information available to the project director and to the crew during the day. On the basis of these alone, no cause for concern was present.

Had soundings been available at regular intervals during the day, and had the results of forecasts based on a consideration of the weather on a larger scale been available at the site, a better appreciation of the problem would have been possible.

Further, even though visual observations were from time-to-time made, low clouds and haze precluded a clear appreciation of the magnitude of the cloud developing over and along the Black Hills. This situation is made clear from time lapse photographs made at the site. As it was, the Project Director had by 1430 MDT been able to identify the type of cloud then forming as a reverse shear. Unfortunately, he did not then appear to be very familiar with the behavior of this type of cloud and therefore did not form an idea of the potential danger at that time. Other weather forecasters, whose experience had been confined to the Great Plains, would have reacted in similar fashion.

The radar observations being taken at the time of the experiments were focused upon a very limited area in which the experiments were being conducted. Therefore, in spite of, or perhaps because of, the sophistication of the experimental design, attention was distracted from the larger problem that was developing.

Had the sky not been so obscured or had a project aircraft been above the lower clouds so that an unobstructed view could have been obtained, or had pilot reports been solicited, these observations would have been useful in evaluating the hazards. The NWS does not usually solicit or use such information in evaluating similar situations.

Even in the face of a dearth of information, Mr. Koscielski and Dr. Dennis did inform the National Weather Service of the potential of the gathering storm at about the time the heavy rains began. Their initiative served, with other information being forwarded by the Air Weather Service and collected by the NWS station to trigger the storm warnings sent by that agency.

The question arises as to whether the seeding should have been conducted at all, or continued beyond the first sortee. From all we can gather, the situation had not reached alarming proportions by the time of the first

launch. By the time of the first seeding, while weather conditions were steadily worsening, the situation was perhaps still suitable for responsible operation. After the first landing, however, the work could reasonably have been secured on the basis of aircraft safety.

The second launch was conducted while it was felt that conditions over the hills were bad enough to preclude safe operations there. Foremost in the minds of IAS personnel was concern over the inability to work aircraft over the Black Hills at that time because of low cloud bases. The decision was made to work to the southeast over the plains and the piedmont in order to continue and because that area had been dry, even though Dr. Dennis had questioned the advisability of continuing in the face of possible flooding (Appendix A).

As the second seeding run was underway, it became clear that a general problem had developed in the northern hills.

Clearly, what was lacking was a steady inflow of information that could have lead to an earlier appreciation of potential danger. Even though the Project Director had good reason to think that his work could not lead to enhanced cloud growth, and even that it probably would not greatly augment the rainfall from such a cloud system, he might properly have secured operations in order to be certain that his work did not create the possible appearance of contributing to a potential flood. There was no prearranged agreement nor any instructions to secure operations in the face of impending danger.

- - - - -

IV. PUBLIC SAFETY

SEEDING SAFEGUARD PROCEDURES

The legislature should alter Chapter 38-9 of the South Dakota statutes to clarify the distinction between professional licenses which are issued to individuals certifying a certain level of their competency and reliability as weather modifiers, and operational permits which authorize licensees to undertake specific operations in given locations under conditions established by the WCC. The state weather control law should give the Commission a clear mandate to issue both licenses and permits, and to establish procedures and criteria for issuance, denial of renewal, refusal to renew, suspension, alteration and revocation of such licenses and permits. The WCC should be empowered to require of licensees, proposing or conducting operations, adequate safeguards which would be designed to preclude both dangerous activity and activity which would, to a reasonable man, create a strong possibility of danger. Each operation should be required to have established in advance definite criteria, arrived at by consideration of hydrologic, agricultural, orographic, demographic, urban, meteorological and other relevant factors, that would lead to identification of conditions requiring a rapid and safe shut down of such operations, until such danger has passed. Operators, when applying for permits, would present such shut down plans to the WCC for its approval.

FLOODING POTENTIAL

Viewed in histroical perspective, the flood of June 9 is one in a long series of similar events. The information in Table 1 has been compiled from various sources including an unsigned report filed in the City Engineer's office, reports by the Pennington County Commission, information assembled by R. P. Hansfield and by the Black Hills Conservancy District. Professor Hulse is researching the subject further and has a manuscript in preparation.

From Table 1 we see that Rapid City has had at least 32 flooding situations in the last 94 years, or roughly one minor incident involving wet streets and flooded basements every three years. Of these, thirteen have been serious and five have been comparable to this years in area flooded, if not perhaps in total discharge. Maps of the flooded zones show that the 1907 flood inundated an area about the same size as did the flood of June 9, 1972. The surface synoptic weather maps for the 1907 bear some semblance to those for 1972, including movement of a cold outbreak southward over the Dakotas, in conjunction with the movement of a trough line, over the Black Hills from the west. Indeed, an easterly wind against the hills was present during the flooding.

Lack of construction in the flood plain in the past apparently precluded extensive property damage or loss of life. Although the City Engineer had had prepared for him in 1964 a summary of these events adequate for engineering purposes, and had made recommendations for handling the flow and for flood plain zoning, there appeared to be little public awareness of this hazard.

TABLE 1.

Floods Affecting Rapid City and Environs - 1878 to 1972

YEAR	DAY	MONTH	ESTIMATED PEAK FLOW-cfs	LOST LIVES	REMARKS
1878	17	April	-	-	Damage slight
1878	21	April	-	-	> $3,000 damage
1878	22	May	-	-	Rapid City, Deadwood, Whitewood
1878	11	June	-	-	Rapid C. rose 10'
1878	9	July	-	1	Rapid C. rose 10', S.Creek 12'
1878	12	July	-	-	-
1883	17-18	May	-	4	Damage Deadwood to Custer est. at $250,000
1885	5	June	12,500	-	Damage >$25,000-Rapid, Box Elder & Elk Creek
1888		May-June	-	-	Light flood
1890	4-5	June	-	-	Heavy rains & floods
1890	17	June	-	-	Flood in Deadwood
1890	10	August	-	-	Considerable damage in Rapid City
1892	6	June	-	-	Damage to railways & roads
1892	12	June	-	-	46 hours of rain,slight damage
1901	22	July	-	-	Streets flooded
1907	12-14	June	13,000	4	> $100,000 Rapid City, $100,000 to railways Canyon Lake dam damaged
1909	25-26	May	-	-	Streets flooded
1909	11-12	June	-	-	Streets flooded, railways damaged
1910	-	August	-	-	-
1920	11	May	>8,000-10,000	8	$200,000 flow estimated at dam 12 miles upstream
1926	26-27	May	-	-	-
1927	-	-	-	-	6½" rain in Belvedire
1929	-	-	-	-	-
1937	17	June	-	-	$200,000 in Hot Springs
1949	15	August	450	-	Large hail storm, $198,000
1952	22	May	2,500	-	-
1962	29	May	10,700	-	-
1962	15	June	-	-	Little damage Aggregate
1962	24	June	-	-	Little damage damage
1962	30	June	-	-	Streets flooded $1,900,000
1962	13	July	10,000	-	Est.$70,000 to public prop.
1972	9	June	13,000-40,000	>230	Estimated $155,000,000

It is clear that a similar flood happens in Rapid City every nine years or so. Considering the local nature of the rains and the number of distinct watersheds in the Black Hills, the occurrence of flash floods over the larger area may well be somewhat more frequent, indeed some 125 have been noted in the Cheyenne drainage over the last century. Thus, flash floods are to be considered a problem in the whole of the Black Hills.

ENGINEERING MEASURES

Canyon Lake Dam, a small earth fill structure on the western edge of Rapid City, quickly filled and then failed due to topping and erosion. It was constructed by the City of Rapid City in 1932 under provision of E.O.7023 W.P.A. It was apparently intended to furnish a recreational lake and water supply. It had a drainage area of 69 square miles and an original capacity of 648 acre feet of flood control storage. By 1964 siltration and debris deposition had reduced this to 216 acre feet. In 1932 the depth was 18 feet, and by 1964 the reservoir had filled with debris to an average effective depth of 8 feet. At the time of the 1964 report, the engineer questioned the stability of the structure and its effectiveness as a flood control device. Indeed, it was strongly advised that the reservoir be emptied, that the silt and debris be removed to an average depth of 30 feet and, among other things, that a ten foot flood storage capacity be retained. It was opined that failure of the dam in the spring of the year could cause a flood as devastating as any in the history of the city.

By 1972, siltration and debris had further reduced the flood control effectiveness of the structure to the point where the rupture of the dam contributed very little to the destruction caused by the flood. The total capacity of 192 acre feet was of little significance in view of the several tens of thousands of acre feet carried by Rapid Creek during the flood.

The present dam is of no use in containing floods, but the dam could be reconstructed for recreational use. One or more larger flood control dams in Dark Canyon would greatly reduce the danger of future floods, as would elaboration of the channel of Rapid Creek by deepening and widening it and by facing the sides with concrete dikes. The dam at Pactola has been successful in preventing small floods and would have helped in this case, except that most of the rain fell between Pactola and Rapid City.

FLOOD PLAIN ZONING

An effective approach would be to institute flood plain zoning in conjunction with engineering measures. The enactment and vigorous enforcement of flood plain ordinances by city, county and regional zoning and planning authorities is essential. Such ordinances can be so drafted as to restrict kinds of use in designated areas in order to protect public health, safety and welfare. The 1907 flood, which was comparable to the 1972 flood in runoff produced, did relatively less harm simply because there was then far less building in the area subjected to flooding. Within the area liable to ten-year flood, it would be appropriate to ban most uses.Figures 1a and

lb dramatically illustrate this point. This could be done by zoning. However, in restricting use of land subject to less frequent flooding it may be constitutionally necessary to resort to the condemnation power and purchase property.

It is noteworthy that, under the National Flood Insurance Act, federally funded insurance for flood losses is available only in areas which have given the federal government satisfactory assurance that adequate land use and control measures have been adopted, with comprehensive criteria for land management and use, and that such measures will be applied as soon as technical information of floodways and on controlling flood elevation is available.

Building code requirements could, if strengthened and enforced, also help mitigate losses. There should be limitation upon types of materials used in areas subject to flooding, imposition of requirements on elevation of structures, and restrictions on construction methods to produce buildings more apt to withstand flooding. For example, many of the homes destroyed in the 1972 flood appeared to be inadequately secured to their footings.

WARNING SYSTEM

Because flash floods present a recurrent hazard to Rapid City and to other communities in the Black Hills, it is important to make a few comments on the warning system.

The first warning, so far as we can determine, that reached the police and public officials came from the sheriff of Lawrence County, Mr. McGrath. When apprised of flooding in Boulder Creek on or about 1800 MDT, he dispatched officers to the scene who immediately evaluated the situation and informed the sheriff, whereupon he notified State Radio. State Radio passed the word to other police officers and to the National Guard.

At 1945 MDT the sheriff called Col. E. Lemaster of the National Guard to warn of flooding. Fortunately, a large contingent of the National Guard was in Rapid City and within 45 minutes some 300 to 400 men had been mustered, organized, and dispatched. By 1045 MDT rescue teams had been dispatched and were at work saving people. By midnight some 800 men were at work and by Saturday morning 3000 men were in the field.

At 1950 MDT the sheriff called again to ask that roads into the mountains be blocked. Men were dispatched but could not penetrate into the hills. City police, sheriffs, and fire department personnel were smoothly alerted by State Radio and responded quickly, competently, and heroically.

Acts of heroism and disregard for personal danger were commonplace that night. The National Guard and the several police agencies acquitted themselves in the highest tradition of humanitarian service. Certainly, the presence of so many National Guardsmen on the scene was a boon to the populace and resulted in the saving of many lives, sadly enough at the expense of some of their own.

At about 2300 MDT Governor Kneip called Col. Barnett, CO of Ellsworth AFB, apprised him of the emergency, and asked for help. Col. Barnett immediately threw the entire available resources of that command into the breech and continued to give all possible aid for the duration of the emergency.

In spite of the efforts of emergency forces, police, National Guard, Air Force, and Civil Defense, it was not easy to warn the populace because of difficulty of movement and widespread flooding. Some people who were warned of personal danger and advised to evacuate did not choose to do so. Some remained in spite of being warned of the risk, and were lost; others came to the scene to observe and in doing so exposed themselves to danger, hampered rescue operations, and in some instances were swept away. Many able bodied citizens, on the other hand, assisted in the rescue on their own initiative.

During the late afternoon, Air Weather Service personnel at Ellsworth AFB had called the NWS to provide periodic updates on the conditions of the cloud developing over the hills because the radar link to the NWS was inoperative, and expressed concern over the possibility of flooding. At about 1715 MDT, Mr. Koscielski called to warn of the possibility of flooding in the northern hills. At 1915 MDT, the NWS issued a warning statement to radio and TV stations in Rapid City, Deadwood, Belle Fourche, and Sturgis to warn of flooding in the northern hills to Elk Creek. No NWS warning was received by State Radio which, under the Civil Defense standard operating procedure, was the agency designated to pass information on to the police, National Guard and other public safety agencies. The only communication between the State Radio and NWS was a call from NWS at 1816 requesting information as to what was taking place between Whitewood and Piedmont. At that time State Radio passed on such information as they had.

NWS did, however, send a warning to the radio and television stations; this was authorized after consultation between the NWS meteorological technicians on duty and Mr. D. Hallagen, meteorologist in charge, who had gone off duty at 1600 MDT.

At about 1800 Dr. Arnett Dennis of IAS called the NWS to inform them of the danger of flooding in the central Black Hills and Rapid City. At 2000 MDT, following a call to Mr. Hallagan who authorized the release, a second warning was issued to the radio and TV telling of flooding danger for Rapid City and Box Elder Creeks. By this time not all media were able to transmit the warning, because some were off the air and because power was out in some sections, precluding reception.

A "hot line" to the five radio stations was activated. Police, if called, were called separately on the regular telephone system.

From what we could learn, the public did not take too seriously the warnings on the public media. Although such warnings are infrequent, and rarely unwarranted, about as much attention is paid to them as to other material on radio and TV. Having become inured to the current style of news reporting, many people are inclined to ignore material not presented in a dramatic way. Inclusion of a message on a moving tape on the bottom of a screen showing other distracting material is not likely to convey the information to a bemused viewer.

The National Advisory Committee on Oceans and Atmosphere has undertaken a project to review and evaluate the nation's flood forecasting and warning program and its performance during Hurricane Agnes which brought death and destruction to the eastern United States later in June 1972. It is clear that the flood forecasting and warning system in the Black Hills area did not function as well as it might have on June 9, 1972.

There is need for restraint in issuing alerts so that false alarms will not mislead the public and undermine its will to respond to warnings. False alarms can be, in themselves, dangerous. Clearly what is needed is a means of obtaining information from the Hills. Remote reading rain and stream gages and a systematic reporting system using people in the Hills to relay information to the NWS would permit NWS personnel to make a proper determination as to whether a warning should be issued. In case of doubt, a warning should be issued.

Present procedures for alerting the populace should be reviewed. Warning of impending disaster should be conveyed to official agencies first, be clearly acknowledged, and then released to the public by state, county or city officials via the usual media. Such notice must forward simple but essential instructions as stated by the authorities and also should inform the public that the authorities will exercise their powers to the extent necessary to enforce the instructions.

The Civil Defense system is geared to catastrophes up to the scale of a nuclear holocaust. It has the potential of serving effectively, and indeed has so served, in minimizing natural disasters. To this end civil defense has an excellent and valuable potential for public service. Exercises designed to optimize the system should be routinely performed.

- - - - -

V. CONCLUSIONS

Our investigation has been far from exhaustive, but is complete enough to permit certain statements that seem to us to constitute a responsible estimate of the situation.

1. Disastrous flash floods occur naturally in the Rapid City area about once every nine or ten years.

2. As the population and development of the city increases, the loss of life and destruction of property will increase with each occurrence unless appropriate measures are taken.

3. Water management and flood control practices will have to be developed to preclude such damage, in addition to flood plain zoning and building code changes designed to minimize loss.

4. The June 9 flood was caused by meteorological conditions beyond the control of man. Indeed the same weather system had produced similar floods from California to South Dakota.

5. Weather modification activities by the IAS did not contribute materially to the flood. Had none been conducted, the damage would have been the same.

6. The statewide effort in rain augmentation conducted by the South Dakota Weather Control Commission was in no way responsible.

7. Regulation, initiated by the Weather Control Commission on a statewide basis, of all weather modification activities is needed to preclude even the appearance of hazardous activity. Operating programs must have available information sources that will permit a safe shutdown of operations and a clearly stated procedure for so doing in the event of a flood threat, regardless of whether or not seeding could contribute to the hazard.

8. The State and IAS weather modification operations should be resumed and continued.

9. The city, county and state police, the National Guard and the personnel of Ellsworth AFB acted quickly, efficiently and properly in doing all that could be done with available resources.

10. State Radio, and the several city, county and state official agencies communicated well and as effectively as they could have.

11. An improved procedure for disseminating storm and disaster warnings to official agencies and to the public is urgently needed, should be firmly established and kept up to date by practice exercises at random intervals.

APPENDIX A

Observations on Rapid Creek Storm of June 9, 1972

(ASD 6/11/72)

At the morning weather briefing at 1015 MDT Alex Koscielski forecast heavy thunderstorms for the Black Hills with some hail to 1.5 in diameter. This forecast was based upon an unstable airmass sounding, a strong flow of moist air from the eastsoutheast against the Hills, and the approach from the southwest of a sharp trough at the 300 mb level. This trough was not so pronounced at 500 mb and we did not have PBA at 500 mb. The day was classified No.3a. The reported p.w. was less than 0.70 inches but this was clearly due to an instrument malfunction, probably related to wetting of the humidity element in rising through the low level moist layer.

I went to the radar station in the mid-afternoon, arriving at 1450. The Baron was just being launched as the first towering cumulus were appearing. At 1504 Case 72-4 of Cloud Catcher was declared on some showers appearing near Black Hawk. It was a salt day and we learned afterward that the random decision was to seed. Salt seeding was accomplished on the southern cells of a shower line which were the test case proper and in the area east of Sturgis as part of an area seed operation. The storm cells moved northwestward and several of them intensified to give local heavy showers. The test case cells gave about 1000 acre feet of rain during the hour. The official test case ended at 1614 and the Baron landed. The maximum tops on the case were around 47,500 feet, which is not extreme for this area.

The Baron was ready to go up again after 1600. Alex and I discussed the advisability of having another case because of the chance of local flooding in the Hills. We decided to call a case on a moderate shower located on the plains about 20 miles east of Hot Springs. We expected it to move northwestward to near Buffalo Gap, an area which reportedly had been quite dry. Salt seeding on these showers continued into the Fairburn area and was conducted from around 1700 to 1730.

Sometime before 1800 we noted that the showers southwest of Sturgis had continued to intensify and that the storm near Fairburn was very strong (67 dBz). Alex talked to the NWS people twice and I called them once to discuss the situation. Their first flash flood warning (for the northern Hills) may have been triggered by one of Alex's calls. In my call I mentioned a strong cell in the Hills west of Hermosa as likely producing one inch hail, heavy rain, or most likely both.

Around 1800 we noted a new and very intense cell covering the general area of Keystone and Pactola. It was not scanned by the computerized radar, but the PPI 10-cm suggested reflectivity factors approaching 70 dBz. The storm near Hermosa was weakening by that time. When the test case finished we ran off the quick recall data and found the test case cell had produced about 4000 acre feet of water, very large but not a record-breaker. We began buttoning up for the weekend, with me leaving the site around 1830 or

a little earlier and Alex leaving around 1900. Apparently there was further organization of the Pactola storm during this period but we still had no idea of the magnitude of what was coming. Alex thought the rains would let up in another two or three hours as a small short wave would pull the activity eastward off the hills.

On the way home I noted the extreme darkness in the western sky. It began to rain at our house around 1900 but not very heavily, and stopped again by 2100. Alex called twice during the evening, the second time about 2030. (We talked again later around 2230.) On our second talk he said that there was a tremendous cloud with almost steady lightning just west of Rapid City and that he estimated the low-level air was feeding into it at 50 mph. He based this estimate on the visible motion of the low clouds. Another cell came up from the south about 2115 and our heaviest rain fell during that time, up to perhaps 2330. During lulls in the rain we could still see the huge storm further west. It had a very flat base which was shown up clearly by the lightning flashes. There was one appendage hanging from it but I am sure it represented strong inflow (scud) and was not a tornado.

With regard to the possibility of seeding adding to the flood:

1. We were on a limited experimental mission with salt, and were not operating as part of the state program as such.

2. No seeding whatever was done on clouds over the Rapid Creek Basin. In fact, no seeding was done over the Hills at all except perhaps west of Piedmont in the early afternoon. We will have to look at the recorded aircraft tracks to be sure.

- - - - -

HOW TO TREAT A PAINFUL PROBLEM OR CLOUDSEEDING ANYONE?

- Anonymous -

Once upon a time in a land characterized by its beautiful fields and energetic people, a painful problem developed. Almost everyone began to suffer from persistent headaches. So pervasive were these headaches that the fields went untended and the economy began to suffer. The wise elders in the land, between headaches, began to consider what might be done. Some thought the public health authorities might be able to help. One knew a doctor, who lived far away in the land of notables and who had become famous for offering unorthodox treatments which other doctors disdained. Still other elders thought the headaches were divinely ordained and advocated prayer. Since the elders could not agree on a single course of action, they decided to pursue all available courses.

The public health authorities sent a doctor who had specialized in headaches to confer with the elders in that part of the land where headaches were most troublesome. He explained that headaches may result from many different causes and that he didn't know all he'd like to know about headaches. He stated that there was a medicine called aspirin that was frequently useful in relieving the pain of headaches, but that it was not a cure for all headaches. Further, there were circumstances when taking aspirin could do harm and that dosages should differ for different circumstances. He suggested that the elders work with their local doctor in administering aspirin selectively to some of the headache sufferers where it was reasonable to expect that the medicine would do them no harm. So saying, he left a supply of aspirin with the local doctor and went back to his office to think about how to cure the headaches in other parts of the land.

"Arrogrant bureaucrat" snorted the elder who knew the famous unorthodox doctor. "Did you notice how indefinite he was about what time the headaches would disappear? He wants to socialize medicine. My friend, the unorthodox doctor, can cure us better and cheaper and we won't have to accept any control from the government. Let's ask my famous friend to come minister to our needs."

And so it came to pass that the famous unorthodox doctor visited the local elders. He was very impressive. He was much handsomer than the government doctor, wore much more expensive clothing, and, best of all, spoke with greater confidence. "I can cure headaches," he stated categorically. "What's more, I alone know how to predict when you are apt to get them. I predict that you will observe an upsurge in headache incidence on the day after St. Patrick's day, the evening of July 4th and the morning of January 1st."

"My methods are safe, simple, direct, effective, and much less expensive than the archaic and expensive approach suggested by that stupid government doctor. Everyone drinks water. Your drinking water comes from deep wells. I will arrange to treat your drinking water with my special type of aspirin. That way, everyone will have some aspirin in his body ready to go to work in case a headache should develop. I alone know the right way to

accomplish this. It involves distribution of aspirin into the soil and subsequent deep percolation to the level where your wells tap the aquifer. I will arrange a network of suitably equipped distribution stations and notify each trained operator by long distance telephone when to administer the treatment."

So saying, he accepted the initial payment on his long-term contract, hired three people whose toilets drained into septic fields, instructed them to flush two aspirin tablets down the toilet whenever he called them from the far off land where the notables lived, and returned home to enjoy the fruits of his labors.

Not all who heard his expertly told tale were prepared to accept it fully. To some his story seemed to have some elements of overstatement in it. To combat the effect of these suspected overstatements, one elder who had formerly been a brain surgeon indulged in compensatory overstatement. Said he," I can show you definite evidence that aspirin won't cure tumors of the brain. People with tumors of the brain have headaches. I don't trust anyone who would advocate reliance on aspirin. They can't tell you the exact biochemistry of aspirin treatment. The government doctor and the famous unorthodox doctor are both relying on aspirin. They are not to be trusted."

The elders who thought headaches to be divinely ordained prayed for an end to headaches and remained dignified and aloof from the controversy.

In time, the headaches became less noticeable. People who had received the government-supplied aspirin thought their headaches had been affected favorably. The sponsors of the unorthodox doctor drank eight glasses of water daily and were convinced that they felt better as a result, even though the water didn't taste any different than it had before. Others felt their prayers had been answered.

And it came to pass in the land characterized by its beautiful fields and energetic people that another painful problem developed. There was widespread drought - - - .

- - - - -